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THE
UPPER CRETACEOUS AND EOCENE FLORAS
OF
SOUTH CAROLINA AND GEORGIA

BY

EDWARD WILBER BERRY

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THE UPPER CRETACEOUS AND EOCENE FLORAS OF SOUTH CAROLINA AND GEORGIA.

By Edward Wilber Berry.

THE UPPER CRETACEOUS FLORA OF SOUTH CAROLINA.

INTRODUCTION.

The following report is the first systematic account of fossil plants from the State of South Carolina. It describes a considerable flora, which clearly demonstrates the Upper Cretaceous age of the deposits in which it is found and which serves to correlate these deposits with the Upper Cretaceous of adjacent States both to the north and to the south.

The present study should be regarded as preliminary in nature, for it is probable that when the Coastal Plain of the State is exhaustively studied many new localities for fossil plants will be discovered and many new species will be added to the Cretaceous flora; not uncommonly Upper Cretaceous floras consist of two or three hundred species. What is already known of the flora of the Middendorf arkose member of the Black Creek formation renders it certain that if additional plant-bearing outcrops are discovered they will yield a large variety of beautifully preserved leaf impressions.

The writer is under obligations to Mr. Earle Sloan, formerly State geologist of South Carolina, and to the United States National Museum for various collections; to Mr. T. W. Vaughan, of the United States Geological Survey, under whom the work has been prosecuted; and especially to Mr. L. W. Stephenson, of the United States Geological Survey, for the care and intelligence with which he has collected fossil plants in this area.

HISTORICAL SKETCH.

The distinction of definitely recognizing the occurrence of the Cretaceous in North America belongs to Lardner Vanuxem,[1] at one time professor of chemistry in the College of South Carolina, who announced its presence in 1829, although John Finch five years earlier had pointed out that part of the "alluvial formation" of Maclure was probably of newer "Secondary" age.[2] In the paper announcing Vanuxem's thesis several Cretaceous localities are mentioned in South Carolina, including Mars Bluff on Peedee River. A number of references to the Cretaceous of the State are contained in the works of Morton, Hodge, and others. Lyell visited the State in 1841–42 and recognized the Eocene age of certain calcareous rocks which had previously been included in the Cretaceous.

At the time of Lyell's visit, or a little later, geologists were well acquainted with the Cretaceous area extending from Cape Fear River in North Carolina to Peedee and Lynches rivers in South Carolina, as is witnessed by Henry D. Rogers's address before the Association of American Geologists and Naturalists at Washington in 1844.[3] All the preceding contributions, however, as well as the descriptions of Cretaceous deposits included by Prof. Tuomey in his Geology of South Carolina, refer exclusively to the fossiliferous marine Cretaceous, which nearly coincides with the present Peedee sand. The large area of Lower Cretaceous beds, as well as the deposits of most of the Black Creek formation, including the Middendorf arkose member, were regarded by Tuomey as of Eocene age and are designated on his geologic map "Sand hills" and "Red Hill area."

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[1] Vanuxem, Lardner, Proc. Acad. Nat. Sci. Philadelphia, vol. 6, 1829, pp. 59–71; Am. Jour. Sci., 1st ser., vol. 16, 1829, pp. 254–256.

[2] Finch, John, Am. Jour. Sci., 1st ser., vol. 7, 1824, pp. 31–43.

[3] Rogers, H. D., Am. Jour. Sci., 1st ser., vol. 47, 1844, p. 252.

South Carolina is not mentioned in Prof. Ward's exhaustive paper on the geographic distribution of fossil plants, published in 1889;[1] nevertheless, a perusal of the older literature shows that the earlier geologic workers occasionally encountered vegetable fossils. They were content, however, merely to mention the fact or to identify the fossils with leaves of trees in the existing flora which they were thought to resemble. For example, Michael Tuomey, in his admirable report on the geology of South Carolina,[2] speaks of "impressions of leaves, in a purplish clay" near Fort Motte on Congaree River and on the same page mentions having encountered—

> on the road, near the head branches of Halfway Swamp, thick beds of sand, containing water-worn nodules of marl and a log of silicified wood, of considerable size. Immediately beneath this is a bed of yellow, tenacious clay, with partings of fine sand and scales of mica. Between the laminæ of the clay we found very distinct impressions of the leaves of the oak, beech, and willow, with their most minute veins preserved. This, and the locality already described, are the only ones known where fossil vegetable remains have been found in the Eocene of the United States, with the exception of silicified wood and lignite, which are everywhere abundant.

This locality is in Orangeburg County and the horizon may possibly represent an Eocene leaf-bearing layer instead of the Cretaceous, for the Claiborne Eocene transgresses the Upper Cretaceous in northern Orangeburg County, and there are no recent records or collections of leaf impressions from this area. On page 154 of the same work, and again on page 211, Tuomey lists silicified wood, lignite, Quercus leaves, Fagus leaves, and Salix, erroneously classing the containing deposits as lower Eocene in age.

Lieber in his first annual report[3] gives considerable attention to what he calls the "brown coal of the Cheraws." He suggests its economic possibilities and records the "bituminized trunk of a tree in a lignite bed," figuring the trunk in his Plate II, figure 8. Lieber also regards these Upper Cretaceous beds as of Eocene age.

More recently Darton made a brief reconnaissance across the State and in a short paper published in 1895[4] records that "plant remains were observed at many points." He made no collections, however, and mentions no localities, and the remark quoted may be taken as one of a general nature. In 1904 Earle Sloan, until recently State geologist of South Carolina, published a report on the clays of that State that shows a most intimate acquaintance with all parts of its Coastal Plain. Fossil leaves are mentioned from three sections of the State,[5] near Aiken, near Middendorf, and at Rocky Point. This report is entirely economic in character, and the author merely records the presence of "dicotyledonous leaves" or identifies them from their resemblance to those of modern species as the leaves of the "elm, ash, cypress, willow, bay, cane, and pine." The containing beds, however, are correctly identified as of Cretaceous age. In 1907 the present writer[6] recorded nine species of characteristic Upper Cretaceous plants from Rocky Point, in Sumter County, contained in the collections of the geological department of Johns Hopkins University. At that time the original collector was not known, but it subsequently developed that the plants had been collected in 1895 by Prof. L. C. Glenn.

In the spring of 1897 Profs. Ward and Glenn visited South Carolina and made large collections from the Rocky Point locality and a small collection from the locality near Darlington. The important localities near Middendorf and in Aiken County had meanwhile been discovered by Earle Sloan, who sent collections from these areas to Prof. Ward. These collections, however, were never studied. In 1906 the writer, in company with L. W. Stephenson, made a canoe trip from Cheraw to the mouth of Peedee River, after which Mr. Stephenson spent considerable time in the eastern part of the State. In 1907 the writer paid a brief visit to the Congaree-Wateree area and collected from the Rocky Point locality. In a canoe trip down

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[1] Ward, L. F., Eighth Ann. Rept. U. S. Geol. Survey, pt. 2, 1889, pp. 663–960.

[2] Tuomey, Michael, Report on the geology of South Carolina, Columbia, 1848, p. 150.

[3] Lieber, O. M., Report on the survey of South Carolina, 2d edition, 1858, p. 94.

[4] Darton, N. H., Bull. Geol. Soc. America, vol. 7, 1896, p. 517.

[5] Sloan, Earle, A preliminary report on the clays of South Carolina, ser. 4, Bull. South Carolina Geol. Survey No. 1, 1904, pp. 26, 76, 104.

[6] Berry, E. W., Johns Hopkins Univ. Circ., new ser., No. 7, 1907, p. 81.

Congaree River during the same year a small collection from the banks of that river was made by Profs. B. L. Miller and M. W. Twitchell. In the spring of 1908 Mr. Stephenson spent some time in the State, making collections from the Black Creek formation of the eastern part of the State as well as from deposits near Middendorf and Langley. Subsequently Mr. Stephenson and the writer made extensive collections from Cretaceous beds near Middendorf and Langley. In 1910 Earle Sloan sent the writer a collection from Miles Mill in Aiken County. All these collections have come into the hands of the writer and are the basis of the present report. The identifiable material is deposited in the United States National Museum.

GEOLOGY OF CRETACEOUS DEPOSITS OF SOUTH CAROLINA.

The Cretaceous deposits of South Carolina form a belt of varying width extending entirely across the State east-northeast and west-southwest. This belt is narrow toward the Georgia line, being only about 20 miles in width at Savannah River, but widens northeast of Black River to nearly 100 miles. Both Lower and Upper Cretaceous deposits are represented.

LOWER CRETACEOUS SERIES.

On the southeastern margin of the crystalline rocks of the Piedmont Plateau, at an elevation of 400 to 500 feet or slightly more, lies a series of white and colored clays, in many places pure kaolins, and of arkosic, locally micaceous, coarse or fine sands with clay balls and, toward the base, subangular pebbles. The deposits are in a few localities lignitic, but no recognizable plant fossils have been collected. The beds dip 50 or 60 feet to the mile toward the southeast and have an estimated thickness of 200 to 300 feet. They constitute the "Hamburg phase" of Sloan, which in the Aiken area is separated by a local unconformity into two divisions, called by Sloan "Lower Hamburg" and "Upper Hamburg." They appear to be continuous with the Patuxent ("Cape Fear") formation of North Carolina and thus to represent the basal formation of the Potomac group of the Maryland-Virginia area. To the southwest they appear to be continuous with the Lower Cretaceous deposits of Georgia, which have been erroneously correlated with the Tuscaloosa formation (Upper Cretaceous) of Alabama by the Georgia Geological Survey. According to the evidence afforded by poorly preserved plants, however, the Lower Cretaceous deposits of Georgia and Alabama appear to be younger than the Patuxent formation of the type region.

UPPER CRETACEOUS SERIES.

BLACK CREEK FORMATION.

Middendorf arkose member.—A somewhat similar series of cross-bedded, varicolored, micaceous, and in many places arkosic sands, containing pebbles, clay balls, and local deposits of nearly pure kaolin unconformably overlies the Lower Cretaceous deposits. These beds, which are here called Middendorf arkose member, are between 100 and 200 feet in thickness and consist to a large extent of reworked Lower Cretaceous materials. They can be traced interruptedly nearly across the State, being transgressed by the Eocene at several points southwest of Lynches River and either replaced by partly contemporaneous deposits of a different character or transgressed by later Cretaceous in the northeastern part of the State. These beds, which constitute the Middendorf formation of Sloan, in places carry a rich and varied fossil flora of Upper Cretaceous age. Along the landward margin of their outcrop their lithologic features are in marked contrast with the characteristic beds of the Black Creek formation, but farther southward, for example, in the Congaree River valley, the Middendorf member commonly exhibits micaceous, lignitic sandy phases, and dark laminated argillaceous phases exactly similar to those of the typical Black Creek but less extensively developed. On the other hand, the Black Creek formation as developed in North Carolina contains a great thickness of light and highly colored cross-bedded sands similar to those of the Middendorf member of South Carolina, and it there covers the time interval of the Middendorf member. The Middendorf therefore has been adopted by the Survey as a member of the Black Creek formation.

Other deposits.—In part later than the Middendorf member and in part contemporaneous with it is a series of dark laminated clays (shales) with sand partings and lenses of micaceous fine-grained sands. These clays, which constitute the Black Creek formation of Sloan, are confined to the eastern part of the State, covering the southern half of Marlboro County, the northwestern part of Marion County, the northern part of Florence County, nearly all of Darlington County, and the southeastern part of Lee County, their areal outcrop being terminated abruptly by the transgression of the Eocene in south-central Lee County. These beds are extensively developed in North Carolina, where they attain great thickness. The lower part of these beds probably represents most, if not all, of the Middendorf sedimentation, as well as that of the period intervening between the close of the Middendorf and the beginning of the Peedee. Fossil plants of genera and species similar to those described from the North Carolina area have been collected from a number of localities in Chesterfield, Florence, and Darlington counties, but the exposures throughout this area are few and poor, owing to the flatness of the country, which is uniformly covered with a mantle of Pleistocene in addition to patches of Eocene and Miocene deposits. The area occupied by these deposits of the Black Creek formation in South Carolina has not been very extensively examined for fossil collections because there is no reason to believe that their flora differs in any respect from that found in the Black Creek formation in the North Carolina area, where the exposures are more plentiful.

As previously mentioned, the Middendorf member in the Congaree Valley contains lenses of micaceous lignitic sands and dark laminated clays like those of the typical Black Creek, indicating that at times the conditions which led to this great thickness of deposits along the north border of South Carolina prevailed farther toward the southwest. Like the Black Creek deposits of North Carolina, these beds of South Carolina are in places glauconitic, and pellets of amber are widely distributed in them.

PEEDEE SAND.

A series of compact sands, in many places fossiliferous, less commonly calcareous, and somewhat glauconitic, conformably[1] overlies the Black Creek formation where it is not transgressed by the Eocene. These sands constitute the Peedee sand, or the "Burches Ferry marls" of Sloan. They extend northeasterly into North Carolina. They are typically marine deposits, carrying the *Belemnitella americana* fauna, and are correlated with the Monmouth formation of the Northern Atlantic Coastal Plain and with the typical Ripley of northeastern Mississippi. They are not known to contain fossil plants in the South Carolina area and are confined to the eastern part of the State, where they are widely distributed, though commonly hidden by various Tertiary or Pleistocene deposits.

DESCRIPTION OF PLANT LOCALITIES.

To supplement the foregoing brief outline of the Cretaceous as developed in South Carolina, a few words may be devoted to the 11 different exposures where fossil plants have been collected.

Localities referred to the Middendorf arkose member of the Black Creek formation are first considered, after which those in the other deposits of the Black Creek formation, in the order of their geographic succession to the southwest, are taken up.

1. Near Middendorf (Field No. 3.7).—This locality is near the Seaboard Air Line Railway, about 2 miles northeast of the town of Middendorf and immediately west of overhead wagon bridge 366. It is just south of the Camden wagon road and about 5 miles east of Big Black Creek. (See Pl. I, *A*.) The following section is exposed in the railroad cut:

Section exposed in railroad cut 2 miles northeast of Middendorf.

	Feet.
1. Surficial sandy loam, sand, and clay	4–10
2. Clay lens containing leaves	0–4
3. Cross-bedded arkosic sands, variegated in color	4–10

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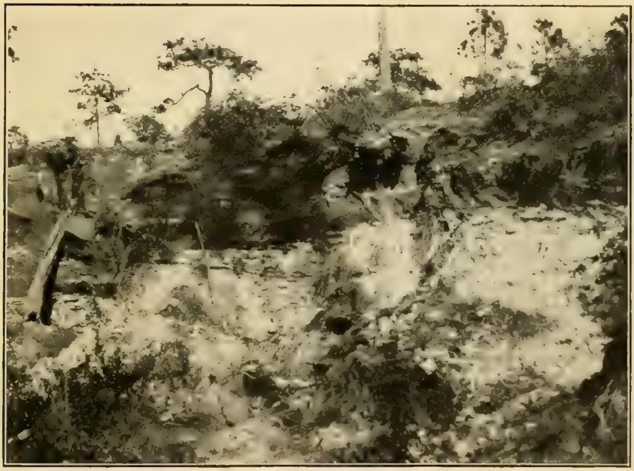
[1] Stephenson records an unconformity, presumably local, in Darlington County (unpublished notes).

A.



B.

PLANT-BEARING CLAY IN MIDDENDORF ARKOSIC MEMBER, BLACK CREEK FORMATION.

A, Near Middendorf, Chesterfield County, S. C.; *B*, Near Langley, Aiken County, S. C.

The leaves are found beneath a ferruginous crust about 3 inches thick, which is local and occurs only above the middle portion of the clay lens. They are for the most part replacements by ferric oxide and make very handsome specimens, the rusty red leaf contrasting against the background of light-buff kaolin, for the bright red of the freshly collected material fades only slightly in drying out. Toward each end of the cut the Pleistocene-Middendorf contact passes downward and disappears below the level of the track. The Middendorf member in this vicinity consists for the most part of sands, with the exception of the one prominent clay lens.

This is the most prolific locality for fossil plants in South Carolina, having furnished 41 of the recorded species. Most of these are splendidly preserved. The following species occur at the Middendorf locality:

Acaciaphyllites grevilleoides Berry.
Andromeda euphorbiophylloides Berry.
Andromeda novæcæsareæ Hollick.
Brachyphyllum macrocarpum Newberry.
Cæsalpinia middendorfensis Berry.
Calycites middendorfensis Berry.
Celastrophyllum crenatum Heer.
Cinnamomum middendorfensis Berry.
Citrophyllum aligerum (Lesquereux) Berry.
Crotonophyllum panduræformis Berry.
Diospyros primæva Heer.
Eucalyptus geinitzi (Heer) Heer.
Eucalyptus wardiana Berry.
Ficus atavina Heer.
Ficus celtifolius Berry.
Ficus crassipes Heer.
Ficus krausiana Heer.
Ficus stephensoni Berry.
Juglans arctica Heer.
Laurus plutonia Heer.
Laurophyllum elegans Hollick.
Laurophyllum nervillosum Hollick.
Leguminosites middendorfensis Berry.
Lycopodium cretaceum Berry.
Magnolia capellinii Heer?
Magnolia obtusata Heer.
Magnolia tenuifolia Lesquereux?
Momisia carolinensis Berry.
Moriconia americana Berry.
Onoclea inquirenda (Hollick) Hollick.
Pachystima? cretacea Berry.
Pinus raritanensis Berry.
Potamogeton middendorfensis Berry.
Proteoides lancifolius Heer.
Proteoides parvula Berry.
Quercus pseudowestfalica Berry.
Salix flexuosa Newberry.
Salix lesquereuxii Berry.
Salix pseudohayei Berry.
Sequoia reichenbachii (Geinitz) Heer.
Widdringtonites subtilis Heer.

By far the most abundant form is *Sequoia reichenbachii* (Geinitz) Heer, of which whole leafy branches, many with their cones attached, are present.

2. Rocky Point (*Field No. 3.1*).—This locality is one-half mile northeast of Sumter Junction, on the Camden division of the Southern Railway, along the eastern scarp of the Wateree Swamp, about 2½ miles east of the river and a short distance east of Beach Creek. The following section is exposed:

Section exposed at Rocky Point.

	Feet.
Pleistocene:	
Sand, coarse, reddish, argillaceous, more or less cemented, with iron crusts below	6
Pack sand, fine, light gray, stratified, becoming more ferruginous below	15–18
Eocene:	
Clay, brownish, laminated, with partings of light-gray sand	6–8
Upper Cretaceous (Middendorf arkose member of Black Creek formation):	
Sand, coarse, white and yellow, ferruginous, becoming very coarse below	5–6
Clay, lens, brownish, laminated	1
Sand, very coarse, ferruginous	4–5
Similar materials, more or less indurated	3–4
Clay, interlaminated, brownish, and clay ironstone with abundant leaf impressions	2
Sand, coarse, brown	2
Clay, laminated, brown, and clay ironstone crusts	3–4
Clay, more massive, weathering to reddish and purple	4–5
Sand, light drab, fine, with some clay laminæ and a few thin ferruginous crusts	10
Clay, light drab	10

The railroad at this point is 115 feet above sea level.

The following 26 species of fossil plants occur at this locality:

Andromeda grandifolia Berry.
Andromeda parlatorii Heer.
Arundo grœnlandica Heer?
Carex clarkii Berry.
Celastrophyllum elegans Berry.
Cinnamomum newberryi Berry.
Crotonophyllum panduræformis Berry.
Cunninghamites elegans (Corda) Endlicher.
Diospyros primæva Heer.
Diospyros rotundifolia Lesquereux.
Eucalyptus geinitzi (Heer) Heer.
Ficus atavina Heer.
Ficus crassipes Heer.
Ficus krausiana Heer.
Hamamelites (?) cordatus Lesquereux.
Heterolepis cretaceus Berry.
Illicium watereensis Berry.
Magnolia capellinii Heer?
Phragmites pratti Berry.
Podozamites knowltoni Berry.
Proteoides lancifolius Heer.
Protophyllocladus lobatus Berry.
Quercus pseudowestfalica Berry.
Quercus sumterensis Berry.
Salix lesquereuxii Berry.
Widdringtonites subtilis Heer.

Of these the various species of Ficus are the most abundant, *Ficus crassipes* Heer and *Ficus krausiana* Heer being especially common and well preserved. *Andromeda grandifolia* Berry and *Protophyllocladus lobatus* Berry are also common, the other species being represented by only a few individuals. This locality stands next to that near Middendorf in the variety of forms represented, but a good many of the specimens were in a rather fragmentary condition before entombment.

3. *About 25 miles below Columbia* (*Field No. 3.3*).—The plants from this locality, which is on the right bank of Congaree River, in Lexington County, are represented by faint impressions in a buff, almost white, micaceous, finely arenaceous, thinly laminated clay, and only the following forms, the majority tentatively identified, are recognizable:

Cinnamomum newberryi Berry (?).
Diospyros primæva Heer (?).
Ficus crassipes Heer.
Ficus krausiana Heer (?).
Salix flexuosa Newberry (?).
Salix lesquereuxii Berry (?).

The two species of Ficus are the most common. Dark laminated lignitic sandy clays along Congaree River in this vicinity show the typical lithology of the Black Creek formation farther to the northeast.

4. *Near Langley* (*Field No. 3.8*).—This locality is just east of the old Augusta road, 1 mile north of the town of Langley and one-half mile west of Langley Dam, on Bighorse Creek, in Aiken County, in a shallow gully which has cut into clay of the Middendorf member to a depth of about 8 feet. The material is a massive, nearly white kaolin ("chalk"), and the leaf impressions, which are not common, are replacements by ferric oxide and show as a rich coffee color against the background of nearly white clay. (See Pl. I, *B*.)

The following 17 species have been identified from this locality:

Andromeda parlatorii Heer.
Araucaria jeffreyi Berry ?
Celastrophyllum carolinensis Berry.
Crotonophyllum panduræformis Berry.
Dewalquea smithi Berry.
Diospyros primæva Heer.
Eucalyptus geinitzi (Heer) Heer.
Ficus crassipes Heer.
Ficus stephensoni Berry.
Laurus plutonia Heer.
Leguminosites robiniafolia Berry.
Myrsine gaudini (Lesquereux) Berry.
Sabalites carolinensis Berry.
Salix flexuosa Newberry.
Salix lesquereuxii Berry.
Salix sloani Berry.
Sapindus morrisoni (Lesquereux MS.) Heer.

All are common, the Dewalquea, Diospyros, Sabalites, and the species of Salix and Ficus being most common and best preserved.

4a. *Miles Mill* (*Field No. 3.11*).—This locality is in northern Aiken County and has not been visited by the writer. The materials and preservation are the same as at the Langley locality, and the collection was made by Earle Sloan, former State geologist. The following species are present in the collection:

Citrophyllum aligerum Berry ?
Crotonophyllum panduræformis Berry.
Dewalquea smithi Berry.
Diospyros primæva Heer.
Quercus pseudowestfalica Berry ?
Salix lesquereuxii Berry.
Salix sloani Berry.

Of these seven species the Dewalquea is by far the most common at this locality. The Crotonophyllum is not rare, but the others are each represented by only one or two specimens.

5. *About 6 miles below Cheraw* (*Field No. 3.10*).—This locality is in Chesterfield County and is represented by characteristic Black Creek materials carrying leaf remains, not in place, but washed upon a river sand bar from some undiscovered Black Creek outcrop in the vicinity. They could not have been carried far because of their character and because this point is at the exact landward margin of the Black Creek formation. Only one recognizable species, *Hedera primordialis* Saporta, is represented.

6. *About 8 miles east of Darlington* (*Field No. 3.2*).—This exposure, on the west bank of Louthers Lake, one-half mile below the ferry, at a spring, shows about 18 feet of dark carbonaceous laminated clay with micaceous and locally glauconitic sand partings. About 1 foot from the top there is a 1-foot layer of lignitic sand and clay balls, and a foot or two below this layer imperfect leaf remains are plentiful. These include a Phragmites-like form and a lanceolate Ficus suggesting *Ficus crassipes* Heer, but the materials are too incomplete for identification. Amber in small drops is present at this outcrop. Louthers Lake is an oxbow of the Peedee, and the above exposure is about 6 miles west of the present river channel and near the eastern boundary of Darlington County.

7. *Right bank of Black Creek* (*Field No. 3.6*).—This locality, 1½ miles east of Darlington and 750 feet south of the Cashua Ferry road bridge, shows a low exposure of characteristic Black Creek materials with poor plant remains. The only recognizable forms are *Araucaria darlingtonensis* Berry, *Ficus krausiana*, and *Strobilites anceps* Berry, although Mr. Stephenson reported seeds of Cephalotaxospermum, which were not found in the material sent in, though very probably they occur here, as they are found along Black Creek in the vicinity.

8. *Cashua Road* (*Field No. 3.4*).—A low, poor exposure of a light chocolate-colored, poorly laminated clay of Black Creek age, containing abundant but much-macerated and rather faint leaf impressions appears just northeast of Darlington, near the foot of the slope leading down to Swift Creek and about 2 rods south of the road. This locality was visited by Ward and Glenn in 1897, and the small collection[1] made by them at that time was sent to Dr. Arthur Hollick at the New York Botanical Garden. The writer examined this collection in New York but failed to find any identifiable forms. The collection made by Stephenson in 1908 contains the following species:

Hedera primordialis Saporta ?
Laurophyllum nervillosum Hollick ?
Magnolia newberryi Berry ?
Myrica elegans Berry.
Proteoides lancifolius Heer ?
Rhus darlingtonensis Berry.
Salix lesquereuxii Berry ?

The last-mentioned form is the most abundant represented in the collection. In addition to plant forms indeterminable casts of invertebrates were found.

9. *Right bank of Black Creek* (*Field No. 3.9*).—About 25 feet of dark carbonaceous clays interlaminated with yellowish, locally indurated, lignitic sand are exposed about 2 miles below Williamsons Bridge in Darlington County. Amber is present, and comminuted plant remains are plentiful and well distributed. The plant material is best preserved within a few feet of the base of the section, and the following forms have been recognized:

Eucalyptus angusta Velenovsky
Ficus krausiana Heer.
Myrica brittoniana Berry.

10. *Ashby's place, 3½ miles northeast of Florence* (*Field No. 3.5*).—This exposure is beside a small branch flowing into Black Creek. Characteristic Black Creek materials at this point yielded the following species:

Algites americana Berry.
Araucaria bladenensis Berry.
Cephalotaxospermum carolinianum Berry.

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[1] The exact locality of this collection was along a ditch north of the road, from the same outcrop

Lignite is abundant, and the clays are full of fragments of indeterminable leaves of dicotyledons. They also contain obscure pelecypod impressions. The materials are dark, laminated, lignitic clays with micaceous sand partings and locally small clay lenses. They are exposed along the branch to a total thickness of 25 or 30 feet, separated into two nearly equal divisions by an intercalated lens of greenish-gray or yellowish rather fine sand with here and there small lenses of dark clay, the sand member being some 20 feet in thickness. Fossil plants occur both above and below the sand lens, detached leaves of the Araucaria being recognizable most commonly.

UPPER CRETACEOUS GEOLOGIC HISTORY OF SOUTH CAROLINA.

The geologic history of that portion of the Upper Cretaceous of South Carolina which has yielded fossil plants is not varied, although it apparently represents a considerable portion of Upper Cretaceous time as a whole. The data upon which the following brief sketch is based are both physical and biologic, and in order to avoid ambiguity of statement the Middendorf arkose member and the other deposits of the Black Creek formation are accorded more or less separate treatment. The deposits of the Middendorf member furnish satisfactory evidence of their origin, the method of their deposition, and the attendant physical conditions. Historically they represent the initial advance of the Upper Cretaceous sea over the coastal lands made up of the Lower Cretaceous arkosic sands and kaolin deposits. This advance was in point of time somewhat later than the initial sedimentation of the Tuscaloosa formation of Alabama, but was probably slightly earlier than the initial deposits of the typical Black Creek sedimentation.

Middendorf time was not of great duration, for the deposits are not thick and were for the most part formed rapidly, as evinced by the current bedding and coarseness of the sands. They represent littoral or beach deposits combined with delta deposits and with estuarine deposits in shallow bays or sounds. Geographically the conditions may be comparable with those in Albemarle and Pamlico sounds of eastern North Carolina, or less closely with those in the quiet estuaries of Chesapeake Bay, where fine-grained muds are being formed in certain areas at the present time. Topographically, however, the parallel is not so close, for the present-day topography is more mature and the relief is slight. Sections drawn across a number of recent bays and sounds along the South Atlantic and Gulf coasts show in some degree what must have been the topography in South Carolina at the beginning of Middendorf sedimentation, except that the modern shores are low. In Middendorf time the Coastal Plain was represented by a comparatively narrow strip of Lower Cretaceous deposits and the eastern flank of the Piedmont was considerably more elevated than it is to-day, so that the earlier deposits of the Middendorf, at least, are more largely sands than the deposits now forming along the seaward margin of the Coastal Plain. These conditions for the Middendorf member may be most simply illustrated by the probable history of a single valley. The Lower Cretaceous surface may be imagined to represent the emerged land surface before the depression or warping or other process that inaugurated the Upper Cretaceous cycle of deposition as it is known to-day. Terrestrial aggradation deposits would be laid down on both valley slopes, and fluviatile or lacustrine deposits would be laid down at some points along its floor. With the changes in relative level the valley would become a bay, estuary, or sound, and the quickened erosion would rapidly build out deltas or alluvial fans along its western margin. This would segregate the coarser sediments, and the finer particles, as well as a large part of the floating carbonaceous matter and minute flakes of mica, would be carried beyond the coarser materials along the shore and ultimately deposited in laminated clays of the Black Creek type. A brief study of similar physiographic deposits of the present confirms the essential correctness of this supposition. The interaction of forces would surely develop some relief of the surface of the sand flats; bars or atolls would be formed from the coarser materials and within the lagoons inclosed by them the kaolins would be deposited. That the sea did not have free access to the area is shown by the complete absence of evidence of marine life in the Middendorf member and other early Black Creek sediments. The fact that remains of terrestrial, fluviatile, or estuarine animals are not found must be attributed to the nature of the sedimentation just outlined. The streams were numerous and more or less torrential in character, piling up their sediments as a series of alluvial fans which finally merged and were completely united by the sediments of the advancing sea. The kaolins were meanwhile deposited in the sheltered basins. Deposits of this kind are rarely fossiliferous, as is evinced by the lack of fossils in other analogous series. The Lower Cretaceous of the Coastal Plain outcrops for several hundred miles along the eastern margin of the Piedmont, but it contains very few fossil plants, and after several decades of exploration not more than half a dozen scarcely determinable shells and a single fragmentary fish have been found in it.

In time the Piedmont river gradients were lessened and river and coastal swamps became more numerous. With continued subsidence such barriers as existed, whether sand bars or islands comparable to the North Carolina "banks," were submerged, and the sediments began to take on a typical marine character and to consist of laminated sands and clays with some glauconite and much vegetable débris derived for the most part from the coastal swamps. Thus sedimentation of the typical Black Creek type commenced considerably earlier toward the North Carolina border than to the southwest—in fact, there are no traces of such sediments in the Aiken area, a condition partly explained by subsequent subsidence in this area and by the profound Eocene overlap. Nevertheless, the much more extensive deposits of kaolin in the Aiken area give evidence of longer-continued, comparatively quiet nonmarine conditions.

The typical Black Creek sedimentation begins a series of deposits which in their origin, character of materials, and contained flora, are strictly comparable with the Magothy and Matawan formations of the northern Coastal Plain, the Black Creek formation of North Carolina, the Eutaw formation of Georgia, and the upper half of the Tuscaloosa formation of western Alabama. Probably also the physiography of the lands adjacent to the places where these sediments were laid down was the same in its general character. All the facts available point to the practical synchroneity of these deposits.

The relief at the beginning of Middendorf sedimentation was considerable; the Piedmont surface, deeply weathered during long ages, had been extensively stripped of the decayed rock which formed the Lower Cretaceous deposits and of the deposits representing the subsequent erosion interval. This removal was not, however, nearly so extensive as many persons have thought. A considerable elevation and erosion interval which follows is represented by the Arundel, Patapsco, and Raritan formations of the more northern Coastal Plain and by the great thickness of marine sediments of at least the upper part of the Lower Cretaceous section in the Texas region. A subsidence or warping at the close of Raritan time inaugurated the South Atlantic cycle of Upper Cretaceous time.

The dip of the Piedmont surface upon which the Lower Cretaceous rests is between 50 and 75 feet to the mile, and though the amount of subsequent warping which may have occurred is not determinable, these figures, however inadequate, furnish some basis for calculating the probable elevation of the Piedmont land surface at the commencement of the Lower Cretaceous epoch. Though the Lower Cretaceous surface suffered considerable erosion before Middendorf time, the beginning of Middendorf sedimentation indicates a second warping with more or less relative subsidence to the eastward and elevation to the westward, so that the general slope may have been nearly as great as it was at the beginning of Lower Cretaceous sedimentation in this area.

The flora as well as the physical conditions show that the Middendorf member and the lower part of the typical Black Creek deposits were formed, in part, at least, at practically the same time. The Middendorf, representing locally the initial basement sands, was probably formed in part on land, or at the point where the Cretaceous rivers reached sea level, or in the sounds or bays which are supposed to have existed. Meanwhile the typical Black Creek sediments were being deposited seaward. As subsidence continued any barriers which may have existed were submerged, especially in the Peedee area, so that practically the whole sedimentation became of the typical Black Creek type and continued long after the close of the deposition of the Middendorf member.

This report does not treat of the subsequent geologic history, which includes the deposition of the immediately succeeding Peedee sand into which the Black Creek formation finally merged and the subsequent reworking of the deposits in the gradual withdrawal of the sea to its various Tertiary and more modern levels.

SYSTEMATIC DESCRIPTION OF THE FLORA.

Phylum THALLOPHYTA.

Genus ALGITES Seward.

ALGITES AMERICANA sp. nov.

Description.—The thallus is preserved in the form of dichotomously divided branches ranging in width from 2 to 5 millimeters, thin and undulating, but evidently rather coriaceous in life, with slightly waved margins. These branches are not preserved for lengths of more than a few centimeters, in which space they are observed to divide only once or not at all. In some specimens they appear to radiate from a common center, but as their proximal parts are invariably missing this supposition can not be verified.

This species is also present in the Magothy formation of Maryland and in the Black Creek formation of North Carolina. The Maryland remains are rare and are in the form of impressions along which recent rootlets have commonly penetrated, giving some specimens the appearance of having midribs. The North Carolina remains, which are abundant in the Black Creek formation at certain localities along Black River, show considerable carbonaceous residuum, indicating that in life the thallus was of considerable consistency.

The name of the genus Algites, to which this form is referred, was proposed by Seward[1] for those fossil remains which are in all probability those of algæ but which from their nature can not be decisively assigned to any established genus.

Fossil algæ are common at some geologic horizons, but their characters are generally ill defined, especially when preserved as impressions, so that comparisons with modern genera altogether lack certainty. As pointed out by Seward for the type of this genus, *Algites valdensis* of the English Wealden, these forms suggest various modern genera, such as Chondrus, Zonaria, Dictyota, and others.

Occurrence.—Black Creek formation, 3 or 4 miles northeast of Florence (Ashby place), Florence County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Phylum PTERIDOPHYTA.

Order FILICALES.

Family POLYPODIACEÆ.

Genus ONOCLEA Linné.

ONOCLEA INQUIRENDA (Hollick) Hollick.

Plate II, figures 7 and 8.

Osmunda obergiana Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 98 (pars), Pl. XXVI, fig. 9d (non figs. 9–9b; Pl. XXXII, fig. 7a).

Caulinites inquirendus Hollick, Bull. New York Bot. Garden, vol. 3, 1904, p. 406, Pl. LXX, fig. 3.

Onoclea inquirenda Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 32, Pl. I, figs. 1–7.

Description.—Remains of this form appear in fragments of fertile fronds, not showing any of the laminæ, which appears to be reduced to short pinnate branches bearing one or more spheroidal bodies which are interpreted as sori. These are uniformly 1.5 millimeters or slightly less in diameter.

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[1] Seward, A. C., Wealden flora, pt. 2, 1894, p. 4.

This species was originally described by Hollick and referred to the genus Caulinites, but was subsequently removed to the ferns because of its close resemblance to the modern genus Onoclea. Earlier figured forms of the same character were associated by Heer with his species *Osmunda obergiana* because they were found in the same beds with the fronds of this species, although they were not found in organic union with the fronds. These fruits are much more like those of the modern forms of Onoclea than they are like those of Osmunda, and they are identical with the type form of the species to which the writer has referred them.

The Long Island and Marthas Vineyard forms have these sori in a single row on each side of an axis and some of the South Carolina specimens seem to have a similar arrangement; others have them definitely in threes, one terminal and two lateral. This latter arrangement also prevails exclusively in the Greenland specimens and in similar material from the Magothy formation of Maryland. This variation is of minor importance and is mentioned simply because it is believed that the grouping in threes is the normal arrangement and that it has been obscured during fossilization in the specimens where it is not clear.

As here understood, this species ranges from the Atane beds of Greenland southward in the Magothy formation of Marthas Vineyard, Long Island, and Maryland, to the locality in South Carolina.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order LYCOPODIALES.

Family LYCOPODIACEÆ.

Genus LYCOPODIUM Linné.

LYCOPODIUM CRETACEUM Berry.

Plate II, figures 1–6.

Lycopodium cretaceum Berry, Am. Jour. Sci., 4th ser., vol. 30, 1910, pp. 275, 276, figs. 1–6.

Description.—These remains consist of fruiting spikes, which are common at the Middendorf locality, 17 specimens having been collected. Spikes loosely imbricated, of modified foliage leaves or bracts. The largest spike, which is nearly complete, is 5 centimeters in length and 5 millimeters in diameter, and is probably somewhat flattened, the bulk of the specimens indicating somewhat smaller dimensions. Axis stout. Bracts several ranked, peduncled, with a cordate or retuse base and an abruptly narrowed acute recurved apex, with an entire margin, each bract subtending a large spheroidal sporangium which may possibly be reniform, though in the impressions preserved in the clays of the Middendorf member it appears to be globular.

Fossil remains of foliage resembling that of the modern club mosses have been frequently described, either as Lycopodium or Lycopodites Brongniart, but the majority of such determinations lack certainty in that they show neither anatomical nor fruiting characters, so that the present species is of great interest as the only post-Paleozoic fossil known to the writer which is referable with absolute certainty to the genus Lycopodium. No remains of foliage have been discovered in these clays which can be correlated with these fruiting spikes.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Phylum **SPERMOPHYTA**.

Class **GYMNOSPERMÆ**.

Order **CYCADALES** (?).

Family **CYCADACEÆ** (?).

Genus **PODOZAMITES** F. Braun.

PODOZAMITES KNOWLTONI Berry.

Plate IV, figure 5.

Zamites angustifolius Eichwald, Lethæa rossica, vol. 2, 1860, p. 39, Pl. II, fig. 7.
Podozamites angustifolius Schimper, Paléontologie végétale, vol. 2, 1872, p. 160 (non Schenk).
Podozamites angustifolius Heer, Flora fossilis arctica, vol. 4, Abth. 1, 1876, p. 36, Pls. VII, figs. 8–11, and VIII, figs. 2e, 5.
Podozamites angustifolius Heer, idem, Abth. 2, 1876, p. 45, Pl. XXVI, fig. 11.
Podozamites angustifolius Heer, idem, vol. 5, Abth. 2, 1878, p. 22, Pl. V, figs. 11b, 12.
Podozamites angustifolius Lesquereux, The Cretaceous and Tertiary floras, 1883, p. 28.
Podozamites angustifolius Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 27, Pl. I, fig. 4.
Podozamites angustifolius Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896,[1] p. 44. Pl. XIII, figs. 1, 3, 4 (non fig. 2).
Podozamites angustifolius Moller, Kgl. Svensk. Vetensk. Akad., Handl., vol. 9, 1903, Pl. I, figs. 8–12, 17b.
Podozamites knowltoni Berry, Bull. Torrey Bot. Club, vol. 36, 1909, p. 247.
Podozamites knowltoni Berry, idem, vol. 37, 1910, p. 182.

Description.—Leaflets elongate, linear-lanceolate in outline, falcate in the single nearly complete South Carolina specimen, 5 to 15 centimeters in length by 0.6 to 1.3 centimeters in greatest width. Base narrowed to a short or obsolete petiole. Apex long pointed. Veins straight and parallel, gradually dying out as they are encroached upon by the narrowing margins, that is, running to the margins and not converging appreciably toward the tip. At 4 centimeters above the base they are 20 in number, and at 2 centimeters below the tip of the specimen figured they are 16 in number.

Fragments of the leaf tissue preserved show that the leaf was comparatively thick and smooth on one surface, presumably the upper, with veins prominent on the other surface. Epidermis seems to be composed of small cells. Holes in a single, more or less imperfect row between the veins may represent stomata that are apparently confined to the lower (?) surface. The outlines of the internal tissue (mesophyll) show large cells longitudinally elongated. This species is suggestive of *Nageiopsis longifolia* Fontaine, of the Lower Cretaceous of Maryland and Virginia, and it may also be compared with a variety of so-called species of Podozamites founded upon detached leaflets of doubtful attribution.

In 1872 Schimper referred the *Zamites angustifolius* of Eichwald to the genus Podozamites, overlooking the fact that four years earlier Schenk had described and named a *Podozamites angustifolius*. The natural impulse would be to dedicate the species here described to Eichwald, but Eichwald has already had a species of Podozamites named for him, in consequence of which the name *Podozamites knowltoni* has been proposed in honor of Dr. F. H. Knowlton, of the United States National Museum. This species has a wide range, both geologically and geographically. It is common in the Jurassic of high latitudes in Russia, Siberia, Bornholm, and Spitzbergen, and it is found in the Upper Cretaceous as indistinguishable remains widely distributed in America, being common in the Dakota sandstone of the West, the Raritan formation of New Jersey, and the Black Creek formation of North Carolina.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

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[1] Although the date on the title-page of this work is 1895, it was not actually published until 1896.

Order CONIFERALES.

Family TAXACEÆ.

Genus PROTOPHYLLOCLADUS Berry.

PROTOPHYLLOCLADUS LOBATUS Berry.

Plate II, figures 9–13.

Thinnfeldia sp. nov. Berry, Johns Hopkins Univ. Circ., new ser., No. 7, 1907, p. 81.
Protophyllocladus lobatus Berry, Bull. Torrey Bot. Club, vol. 38, 1911, p. 403.

Description.—Leaves (phylloclads) of large size, lanceolate or oval in general outline, either entire with crenate margins, rounded apex, and narrowly cuneate base or compound through the development of opposite lateral lobes. Axial vascular strand very stout below, becoming very thin and finally disappearing by repeated branching apically. When the leaves are lobate, subordinate opposite vascular strands form the axis of the lobes, and these also are generally, but not invariably, lost before reaching the tips of the lobes by giving off innumerable secondary branches. Margins in all specimens are rather remotely undulate crenate, and the tips are all rounded. Secondaries numerous and thin, diverging from the main axis of the phylloclad or the axis of the lobes at very acute angles, curving outward, some simple but many dichotomously forked, and a few several times forked. Lobes when present are separated by cuneate, narrowly rounded sinuses which terminate some distance from the main axis. The largest specimen, which is still incomplete both at the apex and at the base, measures 8 centimeters in length and 5 centimeters from tip to tip of the lower lobes, the entire upper portion measuring about 1.5 centimeters in width.

These remains are superficially like fern fronds, especially in specimens which are compound, and were it not for the presence in the Cretaceous of other phyllocladus like remains with a demonstrated gymnospermous structure (for example, Androvettia) their reference to this genus would seem hazardous. The entire specimens are strikingly like some of the forms of *Protophyllocladus subintegrifolius* (Lesquereux) Berry of the Raritan and Magothy formations, or like *Protophyllocladus polymorphus* (Lesquereux) Berry from higher western American horizons, and even the compound specimens have an unlobed apical portion of comparable length which is also similar in appearance to the two species just mentioned. The compound forms are superficially like *Thinnfeldia rhomboidalis* Ettingshausen,[1] the type of the genus Thinnfeldia, whose systematic position has been the occasion of so much controversy and which has been variously regarded as a fern, as a cycad, and as a conifer. The present species shows important differences, however, aside from being much younger, and it is confidently believed to be unrelated to the various older Mesozoic species of Thinnfeldia which have been described.

It may also be compared with various forms from the Upper Cretaceous of Dalmatia discussed at great length by Kerner,[2] who refers them to the genus Pachypteris, which he regards as cycadaceous in nature.

The present species is believed to be closest to *Protophyllocladus subintegrifolius*, a species which is abundant in the Atane beds of Greenland, the Dakota sandstone of Kansas and Nebraska, the Raritan formation of New Jersey, and the Magothy formation from Marthas Vineyard to New Jersey, and which commonly assumes a sublobate form. This is especially shown in unreported collections made by the writer in the Magothy formation of New Jersey. The South Carolina form is common, mostly as fragmentary specimens, at Rocky Point, to which locality it appears to be confined in South Carolina. Regarding the systematic position the writer is confident, despite certain criticisms, that Protophyllocladus is referable to the Taxaceæ. The species is also found in the Magothy formation of Maryland.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. C. Glenn, Ward and Glenn, and E. W. Berry.)

Collections.—U. S. National Museum; Johns Hopkins University.

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[1] Ettingshausen, C. von, Abhandl. K.-k. geol. Reichsanstalt, vol. 1, pt. 3, No. 3, 1852, p. 2, Pl. I, figs. 4-7.

[2] Kerner, F. von, Jahrb. K.-k. geol. Reichsanstalt, vol. 45, 1896, p. 39.

Genus **CEPHALOTAXOSPERMUM** Berry.

CEPHALOTAXOSPERMUM CAROLINIANUM Berry.

Plate III, figure 4.

Cephalotaxospermum carolinianum Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 187.

Description.—Drupaceous fruits, solitary (?), sessile or with an extremely short and stout peduncle, ovoid, somewhat pointed apically and inclined to become slightly cordate below, consisting of an outer fleshy layer and an inner bony layer, as in the Cycadales and Gingkoales; its surface mammillated much as in *Podocarpus elongata* but less markedly so. Bony endocarp ovate-acuminate, immersed in the apical part of the exocarp. Evidently the drupaceous fruit of some Cretaceous member of the Taxaceæ which finds its closest homology in the recent flora in the fruits of Cephalotaxus and certain species of Podocarpus. These drupes have the following dimensions as preserved in a much flattened condition: Length 6 millimeters to 13 millimeters, averaging about 10 millimeters; breadth 5 millimeters to 10 millimeters, averaging about 8 millimeters; thickness about 3 millimeters; fruit in life probably almost circular in cross section. Peduncle short and stout or wanting. Stone ovate-acuminate, lying in the apical part of the fleshy exocarp with the beaked micropylar end reaching almost or quite to the apex. As preserved in a much flattened condition in the clays, these fruits tend to split into two parts, disclosing the bony endocarp or merely a cast of its cavity. The fleshy part of the fruit is carbonized and fails to show any histological details. There is some evidence, or at least a suggestion, in some specimens of the remains of a micropylar canal. Away from the pointed apex the exocarp is 1 to 2 millimeters in thickness, reaching a thickness of 3 millimeters at the chalazal end.

These fruits are very abundant at certain localities in the Black Creek formation in North Carolina, and have also been collected in the extension of this formation near Florence, S. C., and in the lower part of the Eutaw formation in Hale County, Ala.

Fruits referable to the Taxaceæ are extremely rare in the fossil state, as are also remains of foliage which can be referred with certainty to this family. Both Tumion and Cephalotaxopsis from the Lower Cretaceous of Maryland and Virginia are founded upon foliage which seems referable with considerable certainty to this family, and the same strata in those States abound in the foliage referred to the genus Nageiopsis, which seems to be closely related to Podocarpus, so that there is considerable reason for expecting to find Upper Cretaceous representatives of the family in this same general region. Heer[1] describes from the Patoot beds (Senonian) of Greenland a leafy twig with a large solitary fruit, which he calls *Cephalotaxites insignis*, an identification which Solms-Laubach[2] seems to consider probable. Bertrand[3] has described carbonized seeds from the Aachenian of Tournay, Belgium, under the name of *Vesquia tournaisii*, which he considers, because of the arrangement of the vascular bundles, as intermediate between Tumion and Cephalotaxus. It certainly seems to be not without significance that remains of this sort occur at nearly homotaxial horizons in America, Europe, and Greenland.

None of the foregoing, however, are comparable with the present forms, although certain indefinite remains described by Lesquereux as Inolepis sp.,[4] are remotely suggestive of them. It is not believed, however, that they are congeneric.

The general features which seem to indicate a closer relation with Cephalotaxus than with Podocarpus are the absence of the thickened peduncle of the latter and the presence in the same beds with these seeds of foliage described by the writer as *Tumion carolinianum*,[5] which is of the same type as that of Cephalotaxus and may not improbably have been the foliage of the tree which bore the very abundant fruits named Cephalotaxospermum.

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[1] Heer, Oswald, Flora fossilis arctica, vol. 7, 1883, p. 10, Pl. LIII, fig. 12.

[2] Solms-Laubach, Fossil botany, 1891, p. 61.

[3] Bertrand, C. E., Bull. Soc. bot. France, vol. 30, 1883, p. 293.

[4] Lesquereux, Leo, in Hayden's Ann. Rept. for 1874, 1876, p. 337, Pl. IV, fig. 8; The Cretaceous and Tertiary floras, 1883, p. 33, Pl. I, fig. 8.

[5] Berry, E. W., Am. Jour. Sci., 4th ser., vol. 25, 1908, pp. 382–386 figs. 1–3.

The modern genus Cephalotaxus Siebold and Zuccarini, with four species, is confined to the China-Japan region, although it seems evident that it was much more widespread in former geologic times, and to it should probably be referred some of the leafy twigs included in the genus Taxites Brongniart. Fruits of three species of Cephalotaxus, apparently identified correctly, are described by Kinkelin[1] from the upper Pliocene deposits of the Main Valley in Germany.

Occurrence.—Black Creek formation, 3½ miles northeast of Florence (Ashby place), Florence County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Family ARAUCARIACEÆ.

Genus ARAUCARIA Jussieu.

ARAUCARIA BLADENENSIS Berry.

Plate III, figures 6 and 7.

Araucaria bladenensis Berry, Bull. Torrey Bot. Club, vol. 35, 1908, p. 255, Pls. XII, XIII, and XIV, figs. 1–3.

Description.—Foliage dense; phyllotaxy spiral; leaves decurrent, coriaceous, ovate-lanceolate, about 1.6 by 0.8 centimeters, the base rounded, apex thickened, cuspidate; veins immersed, averaging 16 in number, straight, parallel; stomata small, in rows on ventral surface. Leaves ranging from 1 to 2.8 centimeters in length by 0.5 to 1.2 centimeters in width, averaging 1.6 by 0.8 centimeters, obovate in outline, with a broad, rounded base narrowing abruptly and decurrent; the blade broadest about one-third of the distance from the base, above which point it narrows in a short distance to a thickened cuspidate tip; phyllotaxy spiral; leaf substance represented by a sheet of lignite about 0.5 millimeter thick, in which the veins are immersed. These veins average 14 to 16 in number, although some specimens may have as many as 20. They are stout, incurved at the base (forking not observed), becoming parallel and running directly upward until they abut against the leaf margin; that is, they are not convergent toward the tip of the leaf. Although their megascopic appearance is lifelike, their microscopic structure is not preserved.

From one or two places where the specimens are in a more argillaceous matrix it has been possible to get rather inferior specimens showing the arrangement and outlines of the stomata. These are broadly ovate in shape with very thin guard cells, at least when viewed on the surface. They are arranged in somewhat irregular rows on the ventral surface of the leaf, the number of rows between the two veins being generally four. Aside from these facts no other details can be made out.

This species is most remarkably similar to the recent *Araucaria bidwilli* of the Australian region. The resemblance is even closer than the reproductions indicate, a dried herbarium specimen of the latter and a twig of the former when preserved as a brownish impression being practically indistinguishable.

This resemblance in form, habit, and stomatal characters, reenforced by the occurrence of characteristic araucarian cone scales in the same beds at certain localities, renders the identification reasonably conclusive.

The most nearly related form seems to be *Araucarites ovatus*, described by Hollick[2] from the "Cliffwood clay" of New Jersey. The leaves of this form differ merely by their larger size, absence of basal characters, and much less pointed tips; in fact, if the two were found in closer association or if in the abundant material of *Araucaria bladenensis* any specimens had approached *Araucarites ovatus* in size, the writer would be disposed to consider them variants of a single species. As the case stands, it seems better to keep them distinct, for the leaves in the material from the southern Coastal Plain are sufficiently and uniformly different to be readily recognized, and there is the further possibility that the New Jersey species may be more or less closely related to the modern genus Dammara rather than Araucaria.

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[1] Engelhardt, Hermann, and Kinkelin, F., Abhandl. Senckenb. naturf. Gesell., vol. 29, No. 3, 1908, p. 194, Pl. XXIII, figs. 9–13.

[2] Hollick, Arthur, Trans. New York Acad. Sci., vol. 16, 1897, p. 128, Pl. XII, figs. 3a, 4.

A European form which must surely be considered as a nearly related congener of *Araucaria bladenensis* is Saporta's *Araucaria toucasi*, described from the Turonian of Beausset, near Toulon, France.[1] This is strikingly similar to the American species in every respect, and is likewise closely allied, in appearance at least, to the recent *Araucaria bidwilli* of Australia.

Kerner[2] records *Pachyphyllum* (*Pagiophyllum*) *rigidum* Saporta and *Pachyphyllum* (*Pagiophyllum*) *araucarinum* Saporta from the Cenomanian of Lesina, an island in the Adriatic off the coast of Dalmatia, both being originally Jurassic species from the French Corallian of Verdun. Both are very similar to the American species and are of about the same age. The probable identity of Cenomanian and Corallian species seems to the writer extremely doubtful, and in his opinion both Kerner's species should undoubtedly be considered new species of Araucaria, nearly related to, if not identical with, such Cretaceous forms as *Araucaria bladenensis* or *Araucaria toucasi*.

The present species is exceedingly common in and characteristic of the Black Creek formation in North Carolina. In South Carolina it is found in the extension of these beds at the single locality cited. So far as observed, the leaves are always found detached at this outcrop, indicating a large amount of maceration and trituration. They are, however, entirely characteristic.

This species has also been found in the upper part of the Tuscaloosa formation of western Alabama, in the Eutaw formation of western Georgia, and at a somewhat younger horizon near Buena Vista, Ga.

Recently Wieland[3] has described a distinct but comparable species, *Araucaria hatcheri*, from the "Ceratops beds" of Wyoming.

Occurrence.—Black Creek formation, 3½ miles northeast of Florence (Ashby place), Florence County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

ARAUCARIA DARLINGTONENSIS sp. nov.

Plate III, figure 1.

Description.—Seed obovate in outline with broadly rounded apex, straight lateral margins, and somewhat narrowed rounded base, 1.25 centimeters in length and 0.75 centimeter in width across the widest part, 0.50 centimeter wide at base.

This species is based upon the single detached seed figured, which is undoubtedly that of an araucarian conifer. From its size and geologic position it seems probable that it may be a seed of the cone scales described as *Araucaria jeffreyi* Berry, which in turn are probably the cone scales of the leafy twigs described as *Araucaria bladenensis* Berry. No other araucarian remains are, however, associated with this seed at this locality.

Occurrence.—Black Creek formation, right bank of Black Creek, 1½ miles east of Darlington, Darlington County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

ARAUCARIA JEFFREYI Berry (?).

Araucaria jeffreyi Berry, Bull. Torrey Bot. Club, vol. 35, 1908, p. 258, Pl. XVI.

Description.—Cone scales deciduous, rhomboidal, straight sided, thin margined, the apex broadly rounded, with long central apical spur; scales divided by transverse furrow into "ligule" and scale proper; single seeded.

This species was based upon a considerable number of large single-seeded cone scales preserved as impressions and associated with *Araucaria bladenensis* at Big Bend and near the Atlantic Coast Line Railroad bridge over Black River, at points 92 and 87⅝ miles above Newbern on Neuse River, and at Parker Landing on Tar River, all localities in the Black Creek formation of North Carolina. The specimens from Tar River differ somewhat from the others and approximate more nearly the shape of the foliage leaves of *Araucaria bladenensis*, but the scales in general are somewhat variable, as indeed they are from different positions on a single modern Araucaria cone, and it seems likely that they all belong to one species.

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[1] Saporta, G. de, Le monde des plantes, 1879, p. 198, fig. 27.

[2] Kerner, F. von, Jahrb. K.-k. geol. Reichsanstalt, vol. 45, 1896, p. 49, Pl. IV, figs. 1, 3.

[3] Wieland, G. R., Bull. Geol. Survey South Dakota No. 4, Rept. for 1908, 1910, p. 80, fig. 2.

The scales are rhomboidal, the thin lateral margins straight to the point of greatest width, then more or less rounded, produced medially into a long and narrow point. This point is more than a centimeter long in two specimens which still lack the terminal portion. In some specimens the scales are obviously divided by a transverse furrow into the scale proper and the so-called "ligule." They are all preserved as impressions with fragments of lignite representing the scale substance. Except that they do not appear to have been as thick, they are strictly comparable with the typical scales of *Araucaria bidwilli*. In general outline they are also comparable with the scales of *Araucaria cookii* of the Eutacta section of the genus. Seeds have also been found in the Carolina material at this level. From the structure as disclosed in the present impressions it seems obvious that the scales were single-seeded, as in the modern genus, and, taken in conjunction with the foliage just described as *Araucaria bladenensis*, they furnish conclusive evidence of the abundant presence in the middle part of the Cretaceous of eastern North America of true Araucarieæ, thus still further increasing the parallel between the middle Cretaceous floras of this country and those of Europe. Many remains of cones and cone scales have been described as species of Araucarieæ, but it seems scarcely worth while to enumerate them here.

The South Carolina occurrence is based on a single poorly preserved and doubtfully determined specimen. This species also occurs in Georgia.

The Georgia material is neither abundant nor well preserved, but the identifications are unquestionable. A single scale was collected from the Eutaw formation at Chimney Bluff on Chattahoochee River, where it was associated with the abundant leafy twigs of *Araucaria bladenensis* Berry. A single entirely characteristic specimen obtained near Byron, Georgia, is apparently from a higher horizon in the Cretaceous.

Araucaria jeffreyi is extremely close to a form from the Turonian of Priesen, Bohemia, described and named *Araucaria friči* by Velenovsky.[1]

Occurrence.—Middendorf arkose member of Black Creek formation near Langley, Aiken County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Family BRACHYPHYLLACEÆ.

Genus BRACHYPHYLLUM Brongniart.

BRACHYPHYLLUM MACROCARPUM Newberry.

Plate III, figure 2.

Moriconia cyclotoxon Debey and Ettingshausen. Heer. Flora fossilis arctica, vol. 7, 1883, Pl. LIV, fig. 1c (non Heer's other figures).

Thuites crassus Lesquereux; The Cretaceous and Tertiary floras, 1884, p. 32.

Brachyphyllum crassum Lesquereux, Proc. U. S. Nat. Mus., vol. 10, 1887, p. 34.

Brachyphyllum crassum Lesquereux, The flora of the Dakota group, Mon. U. S. Geol. Survey, vol. 17, 1892, p. 32, Pl. II, fig. 5 (non Tenison-Woods, 1883):

Brachyphyllum macrocarpum, Newberry, MSS. name mentioned in footnote. The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 51.

Brachyphyllum sp., Knowlton, Bull. Geol. Soc. America, vol. 8, 1897, pp. 137, 140.

Brachyphyllum macrocarpum Knowlton, Bull. U. S. Geol. Survey No. 163, 1900, p. 29, Pl. IV, figs. 5, 6.

Brachyphyllum macrocarpum Hollick, Bull. New York Bot. Garden, vol. 3, 1904, p. 406, Pl. VII, figs. 4, 5.

Brachyphyllum macrocarpum Berry, Bull. Torrey Bot. Club, vol. 32, 1905, p. 44, Pl. II, fig. 9.

Brachyphyllum macrocarpum Berry, idem, vol. 33, 1906, p. 168, Pl. IX.

Brachyphyllum macrocarpum Berry, Ann. Rept. State Geologist, New Jersey, for 1905, 1906, p. 139.

Brachyphyllum macrocarpum Hollick and Jeffrey, Am. Naturalist, vol. 40, 1906, p. 200.

Brachyphyllum macrocarpum Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 44, Pl. III, figs. 9 and 10.

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[1] In Frič, Archiv naturw. Landesdurchforschung Böhmen, vol. 9, No. 1, 1893, p. 129, text fig. 177.

Description.—Stout twigs with club-shaped, pinnately arranged branches, covered with large, thick, rhomboidal squamate, densely crowded, appressed leaves, attached by practically their whole ventral surface. Phyllotaxy spiral. Leaf surface more or less striated, the striæ converging toward the obtuse apex. Cones not positively determined.

Brachyphyllum is chiefly an older Mesozoic type, but it remains abundant through the Lower Cretaceous, two species having been described from the Potomac group of Maryland and Virginia. It is a waning type in the Upper Cretaceous, where it is represented by the species here discussed and by a variety (see p. 106) which persists as high as the lower Senonian. It is widely distributed and is recorded from Long Island, Staten Island, New Jersey, Delaware, Maryland, North Carolina, Georgia, and Alabama [1] in the East and from the Dakota sandstone of Kansas and the Montana group of Wyoming in the West. It is probably represented in the Patoot beds of Greenland by the material which Heer erroneously refers to Moriconia. Though it is not recorded from Europe, Velenovsky has described remains from the Cenomanian of Bohemia which appear to be identical with the American representatives, referring them to the Jurassic genus Echinostrobus of Schimper.[2] Hollick and Jeffrey have recently shown, from specimens from Staten Island with structure preserved, that this species is related to the subfamily Araucarieæ.

This species is extremely common in the upper part of the Raritan formation at South Amboy, N. J., and in its eastward extension on Staten Island, but has not been collected from any of the plant-bearing horizons of the lower part of the Raritan. Newberry describes large cones which he found associated with these twigs and which he thought were related to them, although this seems improbable. The cones are poorly preserved and their affinities can not be made out. They are very different from previously described cones of Brachyphyllum, and the work of Hollick and Jeffrey would seem to indicate that the present species had small cones. The cones described by Newberry, though here retained in the synonymy of this species, are comparable to the abundant cones from the older Potomac of Maryland which are referred to the form genus Abietites. The single characteristic fragment figured is all that represents this species in the South Carolina Cretaceous, but as it is common in homotaxial deposits in Georgia and Alabama and has also been found in the Black Creek formation of North Carolina no uncertainty is attached to the identification of even such meager material.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Family PINACEÆ.

Genus PINUS Linné.

PINUS RARITANENSIS Berry.

Pinus sp. Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 47, Pl. IX, figs. 5–8.
Pinus raritanensis Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 189.

Description.—This species was discovered in the upper part of the Raritan formation of South Amboy, N. J. The remains consist of slender leaves in fascicles of threes and of poorly preserved winged seeds. Similar remains occur in the Magothy formation of New Jersey and in the Black Creek formation of North Carolina. They are too indefinite to have much stratigraphic value and are of slight botanic interest beyond showing the presence of a pinelike form along the Upper Cretaceous Atlantic coast. In this connection attention should be called to structural material of Pinus from the Raritan formation on Staten Island, N. Y., described by Hollick and Jeffrey [3] as *Pinus triphylla*, which may be identical with the present form.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

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[1] A number of these records are unpublished.

[2] Velenovsky, J., Die Gymnospermen der böhmischen Kreideformation, 1885, p. 16, Pl. VI, figs. 3, 6–8; Květena českého cenomanu, 1889, p. 9, Pl. I, figs. 11–19; Pl. II, figs. 1, 3.

[3] Mem. New York Bot. Garden, vol. 3, 1909, p. 14, Pls. III, figs. 6 and 7 (?), and XXII, fig. 1.

Family TAXODIEACEÆ.

Genus SEQUOIA Endlicher.

SEQUOIA REICHENBACHI (Geinitz) Heer.[1]

Plate IV, figures 1–4

Araucarites reichenbachi Geinitz, Characteristik der Schichten und Petrefakten des sächs.-böhmischen Kreidegebirges, No. 3, 1842, p. 98, Pl. XXIV, fig. 4.
Cryptomeria primæva Corda, in Reuss, Versteinerungen der böhmischen Kreideformation, Abth. 2, 1846, p. 89, Pl. XLVIII, figs. 1–11.
Geinitzia cretacea Endlicher, Synopsis coniferarum, 1847, p. 281.
Sequoia reichenbachi Heer, Flora fossilis arctica, vol. 1, 1868, p. 83, Pl. XLIII, figs. 1d, 2b, and 5a.
Sequoia reichenbachi Heer, idem, vol. 3, 1874, pp. 77, 101, and 126; Pls. XII, figs. 7c and 7d; XX, figs. 1–8; XXVIII, fig. 2; XXXIV, fig. 1; XXXVI, figs. 1–8; and XXXVII, figs. 1 and 2.
Sequoia reichenbachi Lesquereux, The Cretaceous flora, 1874, p. 51, Pl. I, figs. 10–10b.
Sequoia reichenbachi Heer, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 52, Pl. XXVIII, fig. 7.
Sequoia reichenbachi Fontaine, The Potomac or younger Mesozoic flora: Mon. U. S. Geol. Survey, vol. 15, 1890, p. 243, Pls. CXVIII, figs. 1 and 4, and CXIX, figs. 1–5, etc.
Sequoia couttsiæ Hollick, Trans. New York Acad. Sci., vol. 12, 1892, p. 30, Pl. I, fig. 5.
Sequoia reichenbachi Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p, 35, Pl. II, fig. 4.
Sequoia reichenbachi Hollick, Trans. New York Acad. Sci., vol. 12, 1892, p. 30, Pl. I, fig. 18.
Sequoia reichenbachi Nathorst, in Felix and Lenk, Beiträge zur Geologie und Paleontologie der Republik Mexico, 1893, pt. 2, no. 1.
Sequoia reichenbachi Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 49, Pl. IX, fig. 19.
Sequoia reichenbachi Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 59, Pl. XLVIII, figs. 15–18.
Sequoia reichenbachi Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 69, Pl. IV, fig. 8.
Sequoia reichenbachi Berry, idem, vol. 32, 1905, p. 44, Pl. I, fig. 3.
Sequoia reichenbachi Knowlton, Bull. U. S. Geol. Survey, No. 257, 1905, p. 157, Pl. XIV, figs. 3–5.
Sequoia reichenbachi Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 42, Pls. II, fig. 40, and III, figs. 4, 5.
Sequoia reichenbachi Knowlton, Smithsonian Misc. Coll., quarterly issue, vol. 4, 1907, p. 126, Pl. XII, figs. 7 and 8.
? *Geinitzia reichenbachi* Hollick and Jeffrey, Mem. New York Bot. Garden, vol. 3, 1909, p. 38, Pls. V, figs. 7–10; VIII, figs. 3 and 4; XVI, figs. 2–4; XVII, figs. 1–4; XVIII, figs . 1–4.

Description.—The following description was written by Heer in 1868: "S. ramis elongatis, foliis decurrentibus, patentibus, falcato-incurvis, rigidis, acuminatis."

This species has a recorded range on this continent from the Neocomian of Mexico to the Livingston formation of Montana, being very abundant at numerous horizons, and it has likewise been identified from Greenland and Europe. Many investigators have held that some, at least, of these identifications are erroneous, which is probable enough, although the Tertiary *Sequoia langsdorfii* has an almost equally wide range, both geologic and geographic.

In a remarkable memoir recently published Hollick and Jeffrey[2] have described the anatomy of some twigs of the *Sequoia reichenbachi* type from the Raritan formation of Staten Island. According to these authors their results indicate that these remains are Araucarian in their affinity, a view which has been tentatively suggested by numerous students since the days of Geinitz, who referred them to the genus Araucarites. In order to make out a good case these authors were under the necessity of finding Araucarian characters in certain associated cone scales of the sequoia type, as these supposed Araucarian twigs are frequently found with Sequoia-like cones attached to them. They refer these cone scales to new genera which they term Eugeinitzia and Pseudogeinitzia, although the evidence for an Araucarian affinity is in the writer's opinion extremely slender.

As might be expected from their great range, fossils of the *Sequoia reichenbachi* type are of slight stratigraphic value. Nevertheless, the remains are very abundant at the Magothy-Middendorf-late Tuscaloosa horizon, apparently identical in character and commonly cone-bearing, the cones being small prolate spheroids consisting of relatively few peltate umbilicate, sequoia-like scales.

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[1] Only representative citations, chiefly American, of this widespread and persistent species are given.
[2] Mem. New York Bot. Garden, vol. 3, 1909, p. 38, Pl. V et seq.

This species is confined to the Middendorf locality in South Carolina, where it is excessively abundant and commonly cone-bearing. Sequoia twigs are very resistant to maceration and are in many places about the last vegetable remains to disintegrate in marine waters; nevertheless, the excellent preservation at Middendorf of leafy branches of large size with cones attached indicates quiet water and nearness to place of growth. The species is rare in the Raritan formation but common in later Upper Cretaceous outcrops in New Jersey, Delaware, Maryland, North Carolina, Georgia, and Alabama.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by E. W. Berry.)

Collections. U. S. National Museum.

Genus **CUNNINGHAMITES** Presl.

CUNNINGHAMITES ELEGANS (Corda) Endlicher.

Cunninghamia elegans Corda, in Reuss, Versteinerungen der böhmischen Kreideformation, pt. 2, 1846, p. 93, Pl. XLIX, figs 29–31.
Cunninghamites elegans (Corda) Endlicher, Synopsis Coniferarum, 1847, p. 305.
Cunninghamites elegans Heer, Die Flora von Moletein in Mähren, 1869, p. 12, Pl. I, fig. 14.
Cunninghamites elegans Schimper, Paléontologie végétale, vol. 2, 1870, p. 259.
Cunninghamites squamosus Hosius and Von der Marck (non Heer), Die Flora der Westfälischen Kreideformation, Palæontographica, vol. 26, 1880, p. 179, Pl. XXXVII, figs. 137, 138.
Cunninghamites squamosus var. *densifolia* Hosius and Von der Marck, idem, figs. 139–141.
Cunninghamites squamosus var. *linearis* Hosius and Von der Marck, idem, p. 180, fig. 142.
Cunninghamites elegans Heer, Flora fossilis arctica, vol. 7, 1883, p. 17, Pl. LIII, fig. 1.
Cunninghamia elegans Velenovsky, Die Gymnospermen der böhmischen Kreideformation, 1885, p. 14, Pl. IV, fig. 5; Pl. V, figs. 1, 7; Pl. VI, fig. 5.
Cunninghamites elegans Hosius and Von der Marck, Nachtrag, Palæontographica, vol. 31, 1885, p. 227.
Cunninghamia elegans Velenovsky, Sitzungsber. K. böhmischen Gesell., 1886, 1887, p, 634, figs. 1–5.
Cunninghamia elegans Kerner, Jahrb. K.-k. geol. Reichsanstalt, vol. 45, 1896, pt. 1, Pl. IV, fig. 4.
Cunninghamites elegans Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 48, Pl. V. figs. 1–7.
Cunninghamites elegans Hollick, Trans. New York Acad. Sci., vol. 16, 1897, p. 129, Pl. XI, fig. 2.
Cunninghamites (?) sp., Knowlton, Bull. U. S. Geol. Survey No. 163, 1900, p. 29, Pl. V, fig. 3.
Cunninghamites elegans (?) Fliche, Bull. Soc. sci. Nancy, 1900, p. 10, Pl. I, fig. 1.
Cunninghamites elegans Hollick, Bull. New York Bot. Garden, vol. 2, 1902, p. 402, Pl. XLI, fig. 11.
Cunninghamites elegans Berry, idem, vol. 3, 1903, p. 64.
Cunninghamites elegans Zeiller, Annales des mines, March, 1905, p. 15, Pl. VII, fig. 4.
Cunninghamites elegans Knowlton, Bull. U. S. Geol. Survey No. 257, 1905, p. 135, Pl. XV, fig. 1.
Cunninghamites elegans Hollick, Mon. U. S. Geol. Survey, vol. 50, 1907, p. 41, Pl. III, fig. 1.
Cunninghamites elegans Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 70, Pl. III, figs. 7–9, 11.

Description.—The following is the description by Corda in 1846:

> C. ramis gracilibus teretibus, pulvinulis foliorumr homboideo-hexagonis, longitudinaliter carinatis; cicatricibus terminalibus oblique-transversis; foliis hamato-arrectis, attenuatis, integerrimus, acutis, medio nervo tenui simplici.

The type locality for this handsome species was the "*Untern Quader von Masseno bei Schlan in Böhm.*" Since its description by Corda it has been recorded from a number of European and American localities. Abroad it is found from the Cenomanian to the Emscherian in Bohemia, Moravia, Westphalia, Dalmatia, and Bulgaria. In America it occurs in the Magothy formation from Marthas Vineyard to New Jersey, ranging northward to the Patoot beds of Greenland. In the West it has been found in the Montana group, both in Montana and in Wyoming. Exceptionally large forms of this species are abundant in the upper beds of Black Creek formation of North Carolina, and the species is also present at a somewhat higher Upper Cretaceous horizon near Byron, Ga. Abroad the species has been recorded by Schenk from the Urgonian and by Fliche from the Barremian, but the latter identification is probably and the former almost certainly incorrect.

The South Carolina material is scanty and fragmentary. It comes from the Rocky Point locality and is queried because the ferruginous replacement renders the identification uncertain. The remains are those of long, rather slender, curved leaves of the *Cunninghamites elegans* type, the single specimen and its counterpart representing the distal portion of a twig about the normal size for this species but somewhat smaller than the specimens from the Black Creek formation of North Carolina.

The genus Cunninghamites was proposed in 1838 by Presl[1] in Sternberg's great work, and *Cunninghamites oxycedrus* from the Quader of Niederschoena in Saxony was designated the type by Brongniart[2] in 1849. Several fossil species of Cunninghamites have been described, and recently structural material of a cone very close to that of the existing Cunninghamia has been described[3] from the Upper Cretaceous of Japan. The existing species of Cunninghamia, two in number, inhabit the subtropical uplands of the Orient.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. F. Ward and L. C. Glenn.)

Collections.—U. S. National Museum.

Family CUPRESSEACEÆ.

Genus WIDDRINGTONITES Endlicher.

WIDDRINGTONITES SUBTILIS Heer.

Plate II, figures 14–17.

Widdringtonites subtilis Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 101, Pl. XXVIII, fig. 1, *b*.

Widdringtonites subtilis Heer, idem, vol. 6, Abth. 2, 1882, Pls. VII, figs. 13 and 14, and XXVIII, fig. 4, *b*.

Widdringtonites subtilis Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 57, Pl. X, figs. 2–4.

Widdringtonites reichii Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 58, Pl. III, fig. 8.

Widdringtonites subtilis Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 45, Pl. IV, figs. 2–5.

Widdringtonites reichii Berry, Johns Hopkins Univ. Circ., new ser., No. 7, p. 81, 1907.

Widdringtonites subtilis Berry, Bull. Torrey Bot. Club, vol. 39, 1912, pp. 341–348, Pls. XXIV, XXV.

Description.—This species was described from the Atane beds of Greenland by Heer in 1874. His material was, however, extremely limited. Subsequently it was found in considerable abundance in the Raritan formation of New Jersey and still more recently Hollick has recorded it from Marthas Vineyard and Block Island (Magothy formation). It may be questioned if some of the coniferous material described by Velenovsky from the Bohemian Cretaceous under other names should not be compared with the present form. It is even more slender than *Widdringtonites reichii*, with much shorter twigs, which have the appearance of having been somewhat lax in habit. The leaves are usually more elongated, close set, and appressed, narrowly lanceolate, straight and scalelike; they are said by Heer to be somewhat spread and falcate proximad. Remains of this latter sort occur in the Tuscaloosa formation of Alabama and the Magothy formation of Maryland.

Newberry mentions a vague cone about 1 centimeter in diameter as included in the Raritan material. The writer has not seen this specimen but has found a number of poorly preserved detached cones among the abundant remains of this species in the Cretaceous beds of South Carolina and a number of specimens with attached cones from the Tuscaloosa formation in western Alabama, where this species is exceedingly abundant at certain localities. These cones are terminal, roughly spheroidal in outline, and apparently consist of four thick scales with wide blunt tips and somewhat extended bases. They are closely comparable to the cones from the Cretaceous of eastern Europe ascribed to *Widdringtonites reichii* by Velenovsky and Krasser. (See Pl. II, figs. 18 and 19.) These authors refer this form directly to the genus

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[1] Sternberg, Kaspar, Flora der Vorwelt, vol. 2, Nos. 7 and 8, 1838, p. 203.

[2] Brongniart, Tableau, 1849, p. 68.

[3] Stopes and Fujii, Phil. Trans. Roy. Soc. London, vol. 201 B, 1910.

Widdringtonia, and it would seem that the cones attached to the Alabama specimens of *Widdringtonites subtilis* conclusively demonstrate its relationship with some of the modern species included in the genus Callitris by Eichler.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; Rocky Point, Sumter County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Genus **MORICONIA** Debey and Ettingshausen.

MORICONIA AMERICANA Berry.

Plate VII, figures 1–4.

Moriconia cyclotoxon Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 65, Pls. XLIII, fig. 4, and XLVIII, figs. 1–4 (non Debey and Ettingshausen).

Moriconia cyclotoxon Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 70; vol. 33, 1906, pp. 165–167.

Moriconia americana Berry, idem, vol. 37, 1910, pp. 20, 186.

Description.—Leafy twigs, apparently deciduous in habit, bifacial, phylloclad-like, consisting of cyclically arranged reduced leaves. Along the main axis on each flat face of the branch these leaves are relatively and closely appressed, with a narrow base and a broad semicircular apex. The corresponding lateral pairs of leaves are thin and pointed and transversely compressed. In the axis of each of these marginal leaves is a reduced branch flattened in the same plane as the main branch, so that the whole arrangement is strictly opposite and distichous. These reduced lateral branches have leaves of the same character and arrangement as those of the main branch. The bifacial leaves are, however, somewhat smaller and blunter and the marginal leaves are broader and less acute. In a short distance they become smaller distad, generally not more than five or six pairs being required to complete the blunt lateral reduced twigs. The main vascular axis is stout and in some specimens a vascular axis can be made out in the lateral branches. The leaves do not show any veins. The texture was apparently coriaceous, but from the appearance of the majority of specimens the leaves were thin. No structural material or indications of fruits or fruiting characters have been discovered. This species, formerly confused with *Moriconia cyclotoxon* of Debey and Ettingshausen, differs from the latter, which is the type and only other known species of the genus, in being more phylloclad-like and strictly comparable to a cupressineous genus like Libocedrus. It is also about twice as large, the lateral twigs are more reduced, and the main axis is invariably leafy. It differs also in its geologic range, the two species not being anywhere contemporaneous in America, although the type in Europe extends as high as the later larger form of America.

Superficially these remains closely resemble fragments of fern fronds. In fact, Debey, the original discoverer, always insisted that they were ferns and Heer described the earliest collected and poorly preserved remains from Greenland as a species of Pecopteris. There can be no doubt, however, of their gymnospermous nature. For stratigraphic determinations they are one of the most characteristic fossil plants known, as the geometrically arranged outlines of the leaves is recognizable with certainty in the smallest fragment.

They are strikingly like the curious genus Androvettia, which was recently described by Hollick and Jeffrey[1] and referred by them to the Araucarieæ, although Moriconia has, on the evidence of the foliar characters, been invariably referred to the Cupressineæ. The present species is common at the Middendorf locality in South Carolina and is a characteristic post-Raritan species in the Atlantic Coastal Plain, having been recorded by the writer from numerous localities in the Magothy formation of New Jersey, Delaware, and Maryland, and from the Black Creek formation in North Carolina. *Moriconia cyclotoxon*, the type of the genus, is confined to the Raritan in this country, although it is found in both the Atane and Patoot beds of western Greenland and came originally from the Senonian of Prussia.

Occurrence.—Middendorf arkose member of the Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

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[1] Hollick, Arthur, and Jeffrey, E. C., Mem. New York Bot. Garden, vol. 3, 1909, p. 22, Pl. III, figs. 1–5, etc.

CONIFERÆ INCERTÆ SEDIS.

Genus STROBILITES Lindley and Hutton.

STROBILITES ANCEPS sp. nov.

Plate III, figure 5.

Description.—Cone a prolate spheroid in shape, about 3 to 4 centimeters in length by 2.4 centimeters in diameter, made up of spirally arranged, rather thick, flat, obovate scales. The condition of preservation of these cones, of which two were collected, is such that their generic or even tribal affinity can not be determined; hence they are referred to the comprehensive form genus Strobilites. They are not of the Sequoia or Widdringtonia type and resemble certain cones of the Pinus more than they do any of the other coniferous genera represented by foliage in the South Carolina Cretaceous. They are similar to the much more elongated cones from the Lower Cretaceous of the Atlantic Coastal Plain, which have been referred to the form genus Abietites, and are not at all like the assorted conelike remains described by Hollick and Jeffrey from the Raritan formation as forms of Strobilites. As regards size the South Carolina cones are comparable to *Strobilites inquirendus* Hollick from the Magothy formation of New Jersey, but the preservation of the latter is so poor that the specimens are almost valueless.

A comparison which is entitled to some weight may be made with the cones described by Ettingshausen from the Upper Cretaceous of Saxony and identified as *Cunninghamites sternbergii.*[1] Whatever may be the true botanic affinity of these fossils, they are almost certainly cogeneric with those from South Carolina with which they are in close agreement.

Occurrence.—Black Creek formation, right bank of Black Creek, 1½ miles east of Darlington, Darlington County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Genus HETEROLEPIS gen. nov.

HETEROLEPIS CRETACEUS sp. nov.

Plate III, figure 3.

Description.—Cone scale of large size, about 3 centimeters in length, with a stout, woody axis 5 millimeters wide at the base and 1.3 centimeters wide where it expands to form a bosslike, slightly umbilicate tip which is evenly rounded, forming a right angle with the axis; in outline almost circular, with a slightly irregular striated margin, 1.7 centimeters in diameter.

This species is based upon the single specimen figured, which is so characteristic that it is likely to be a valuable stratigraphic fossil, although its botanic affinity can not be determined. It may be cycadaceous or it may belong to a large-coned species comparable with the remains commonly referred to Sequoia or Geinitzia.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. C. Glenn.)

Collections.—U. S. National Museum.

Class ANGIOSPERMÆ.

Subclass MONOCOTYLEDONÆ.

Order NAIADALES.

Family NAIADACEÆ.

Genus POTAMOGETON Linné.

POTAMOGETON MIDDENDORFENSIS sp. nov.

Plate IV, figure 6.

Description.—Leaves of small size, entire, obovate lanceolate or spatulate in outline, about 4 centimeters in length by 1.45 centimeters in greatest width, which is in the apical half of the leaf. Petiole short and broad. Venation fine, immersed, acrodrome.

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[1] Ettingshausen, C. von, Die Kreideflora von Niederschoena in Sachsen, 1867, p. 12, Pl. I, figs. 4–6.

This species is based upon the single specimen figured and its counterpart, which may be interpreted as the remains of two leaves in juxtaposition or of a single leaf in which the upper and lower cuticle has parted company. The latter appears to be the most reasonable explanation. The species was evidently aquatic, and it is very close to certain modern species in this genus. It also suggests the genus Pistia, of which a typical species is common in the Black Creek formation of North Carolina. It is quite distinct from the latter, however, and seems to be an immersed leaf of a Potamogeton in the sum of its characters.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order POALES.

Family POACEÆ.

Genus ARUNDO Linné.

ARUNDO GRŒNLANDICA Heer (?).

Plate IV, figure 7.

Arundo grœnlandica Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 104, Pl. XXVIII, figs. 8–11.
Arundo grœnlandica Heer, idem, vol. 6, Abth. 2, 1882, p. 57, Pl. XVII, fig. 10.
Arundo grœnlandica Heer, idem, vol. 7, 1883, p. 18, Pl. LIV, figs. 1–3.

Description.—Fragments of long, linear, pointed leaves, about 2.5 centimeters in greatest width. Primaries numerous, parallel, fine, about 2.5 millimeters apart, separated by numerous very fine parallel secondaries; the central primary apparently somewhat enlarged to form a midrib.

In the Greenland material this species included culms as well as leaf fragments. The South Carolina material is queried because it differs from the type in having a midrib, which is not, however, so prominent a feature as the drawings indicate, having been accentuated by the method of preservation, replacement by iron oxide. It may be compared with various described fragments of monocotyledonous leaves referred to this genus and to Phragmites and a variety of other genera of the Poales. There is the further possibility that these remains may represent fragments of the rays of some palm. They are of slight botanic interest but are present in well-marked specimens at the Rocky Point locality and may be found to possess considerable stratigraphic value.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. C. Glenn.)

Collections.—U. S. National Museum.

Genus PHRAGMITES Trinius.

PHRAGMITES PRATTII Berry.

Phragmites sp. Berry, Bull. Torrey Bot. Club, vol. 34, 1907, p. 190, Pl. XI, fig. 5.
Phragmites prattii Berry, idem, vol. 37, 1910, p. 191.

Description.—Parallel-veined, monocotyledonous leaf fragments, indicating grasslike leaves 1 centimeter or more in width, having about ten equal parallel veins and a few fine transverse veinlets. Leaf substance thin.

This species is strictly comparable with a large number of fossils that have been referred to Phragmites, which must be regarded as purely a form genus for the reception of fragments of the leaves of grasses or sedges. The present species, which has been detected at a number of localities in the Black Creek formation of North Carolina, has been collected only at the Rocky Point locality in South Carolina, where small fragments are common. It occurs also in the basal beds of the Eutaw formation along Chattahoochee River.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. F. Ward and L. C. Glenn.)

Collections.—U. S. National Museum.

Family CYPERACEÆ.

Genus CAREX Linné.

CAREX CLARKII Berry.

Carex clarkii Berry, Am. Naturalist, vol. 39, 1905, p. 347, fig. 1.
Carex clarkii Berry, Ann. Rept. State Geologist New Jersey for 1905, 1906, pp. 138–141.
Carex clarkii Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 169.
Carex clarkii Berry, Johns Hopkins Univ. Circ., new ser., 1907, No. 7, p. 81.

Description.—Leaf fragments, the largest being 6 centimeters in length, varying in width from 1.5 millimeters to 4 millimeters, averaging between 2 millimeters and 3 millimeters, slightly keeled, becoming thicker and narrower proximad. Midrib moderately prominent. Lateral veins, which are parallel with it, very fine and scarcely discernible except in the larger specimens.

In common with other fossil remains of grasses and sedges this species has no botanic value except as an indication of the presence of plants of these families. It has, however, like so many fossils of vague botanic affinities, considerable stratigraphic value, as it is found to characterize the Magothy formation at a large number of outcrops from New Jersey to Maryland. The South Carolina remains are not abundant and are confined to the Rocky Point locality.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. C. Glenn.)

Collections.—U. S. National Museum.

Order ARECALES.

Family PALMÆ.

Genus SABALITES Saporta.

SABALITES CAROLINENSIS sp. nov.

Plates V and VI.

Description.—A fan palm with very large flabellate leaves. Rays numerous, keeled proximad, becoming nearly flat distad, ultimately splitting more or less. Petiole not preserved in any of the collected material, which includes abundant but fragmentary specimens. Primaries stout and prominent, as much as 1.2 centimeters apart in the largest specimen. Secondaries usually seven in number between each pair of primaries, with which they are approximately parallel; thin, connected by numerous ill-defined cross veinlets.

This was evidently a very large Sabal-like leaf, of which the largest collected specimens are those figured. All the material comes from the single locality near Langley, though very small fragments of what appears to belong to a palm have been detected at several other localities in the South Carolina Cretaceous. These may represent this species, but they are too unrepresentative to be even tentatively identified with it.

The enormous number of existing palms, which includes considerably more than one thousand species, is about equally divided between the oriental and occidental tropics, with many monotypic genera, showing well the marked effects of geographic distribution and isolation on the formation of species. There are no outlying forms, the highest northern latitude reached being about 43° in Europe and the highest southern latitude about 45° in New Zealand.

Lesquereux writing in 1878 [1] records fossil palms in 52° north latitude in both America and Europe. Since then remains have been described from as far north as 80° (Grinnell Land, Spitzbergen), and two fine species are recorded from the earlier Tertiary of Greenland (latitude 70°). A variety of Paleozoic remains has been referred to the Palmæ, these remains ranging in their botanic affinities from Stigmaria trunks to Cordaitean leaves and fruits. The nature of the latter was first rightly conjectured by Brongniart in 1828. With the marvelous increase, during the last 25 years, in knowledge of the vegetation of the Paleozoic, it can now be positively affirmed that palms are unknown from pre-Mesozoic formations.

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[1] The Tertiary flora, 1878, p. 109.

Stenzel, who has recently monographed[1] the fossil palm wood of the world, finds the oldest known wood to come from the Turonian of France (one species), the succeeding Senonian terrane yielding six species. At the beginning of the Tertiary period the species became numerous.

Undoubted remains of palm leaves occur somewhat earlier, the middle part of the Cretaceous, in the light of present knowledge, marking the introduction of the type. The Cenomanian of Europe has furnished undoubted palm leaves (upper Cenomanian of Tiefenfurth in Silesia), and Stur[2] has described fruit from that horizon in Bohemia. Fliche has described three species in two genera from a similar horizon in France.[3] The Senonian deposits show species in a variety of genera. It is in the Tertiary, however, that palms become greatly developed and widespread, and the numerous species found on evidence afforded by stems, leaves, petioles, fruits, and even flowers are referable to a large number of genera (Geonoma, Manicaria, Calamopsis, Thrinax, Phœnix, Nipa, Chamærops, Oreodoxites, Sabal, Iriartea, Latanites, and the like). In this country the earliest known remains are those small fragments of striated leaves, of a rather doubtful nature, which Lesquereux described[4] as *Flabellaria minima* from the Dakota sandstone.[5]

The Montana group of Senonian age has furnished Knowlton[6] with the undoubted remains of a large palmetto-like form (Sabalites),[7] and the Laramie formation furnishes a number of species, some of which, represented by both leaves and fruit, continue into the Eocene.

The present species may be compared with *Sabalites magothiensis* Berry,[8] which is found in the Magothy formation from Raritan Bay in New Jersey to Severn River in Maryland. The two species are entirely distinct, however, and the South Carolina form is much better characterized and represented by more complete material.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley, Aiken County. (Collected by Earle Sloan, E. W. Berry, and L. W. Stephenson.)

Collections.—U. S. National Museum.

Subclass DICOTYLEDONÆ.

Order JUGLANDALES.

Family JUGLANDACEÆ.

Genus JUGLANS Linné.

JUGLANS ARCTICA Heer.

Plate VIII, figures 1 and 2.

Juglans arctica Heer, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 71, Pls. XL, fig. 2; XLI, fig. 4c; XLII, figs. 1–3, and XLIII, fig. 3.

Juglans arctica Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 68, Pls. XIX, fig. 3, and XXXIX, fig. 5.

Juglans arctica Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 62, Pl. XX, fig. 2.

Juglans arctica Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 58, Pl. III, fig. 7.

Ficus atavina Hollick, Trans. New York, Acad. Sci., vol. 11, 1902, p. 103, Pl. IV, fig. 5.

Juglans arctica Berry, Ann. Rept. State Geologist New Jersey for 1905, 1906, p. 139, Pl. XXI, fig. 1.

Juglans arctica Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 170.

Juglans arctica Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 54, Pl. IX, figs. 6–8.

Description.—The following is the description of Heer, written in 1882:

I. Nuce ovali, 34 mm. longa, 17 mm. lata; foliis magnis, foliolis ovalibus, basi inæquilateralibus, integerrimis, nervo medio valido, nervis secundariis angulo semirecto egredientibus, curvatis.

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[1] Beitr. Pal. v. Geol. Oesterr.-Ungarn., 1904, pp. 1–182, Pls. I–XXII.

[2] Verhandl. K.-k. Geol. Reichsanstalt Wien, 1873.

[3] Études sur la flore fossile de l'Argonne, 1896.

[4] Cretaceous flora: 1874, p. 56, Pl. XXX, fig. 6.

[5] It is now definitely decided that Hollick's supposed palm, Serenopsis, from the Cretaceous of Long Island, is a Nelumbo.

[6] Bull. U. S. Geol. Survey No. 163, 1900, p. 32.

[7] Dawson has also described a Sabal from the Upper Cretaceous at Nanaimo.

[8] Torreya, vol. 5, 1905, p. 32.

The leaves of this species vary considerably in size and outline, as might be expected in this genus. Heer's type material is somewhat imperfect and some of it is difficult to distinguish from some of the forms referred to the same author's *Juglans crassipes*, although the latter is on the whole a much larger less oblong form with a narrower base. *Juglans arctica* is oblong-ovate in outline, with an obtusely pointed apex and a rounded, generally inequilateral base. The petiole and midrib are stout. Secondaries numerous, well marked, parallel, camptodrome. Size varies in complete specimens from 9 to 15 centimeters in length and from 3 to 6 centimeters in width.

A nut and catkins are associated with the leaves at the type locality in the Atane beds of Greenland, which confirm their reference to this genus. A single leaf is recorded from the Raritan formation of New Jersey, and the species also occurs in beds of this age on Staten Island. With these exceptions the species is confined to later horizons, occurring in the Magothy formation on Marthas Vineyard, Block Island, and in New Jersey, in the Black Creek formation of North Carolina, and in the Middendorf arkose member of the Black Creek formation of South Carolina. In the West this species occurs in the Dakota sandstone of Kansas. Its occurrence in South Carolina is based on the basal halves of characteristic inequilateral leaves of rather small size.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County, Rocky Point, Sumter County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order **MYRICALES.**

Family **MYRICACEAE.**

Genus **MYRICA** De Candolle.

MYRICA BRITTONIANA Berry.

Plate VII, figures 17 and 18.

Myrica heerii Berry, Am. Naturalist, vol. 37, 1903, p. 682, figs. 7, 8 (non Boulay).
Myrica brittoniana Berry, Bull. Torrey Bot. Club, vol. 32, 1905, p. 46.

Description.—Leaves elongate-lanceolate in outline, 13 to 14 centimeters long by 2.7 centimeters in greatest width, which is in the middle part of the leaf. Apex elongated, narrowed, bluntly pointed. Base attenuated. Margin entire, or entire below and undulate or distantly and obtusely toothed above. Texture coriaceous. Petiole and midrib fairly stout. Secondaries thin, immersed, generally obsolete, branching from the midrib at rather large angles, comparatively straight, camptodrome.

This striking species was described by the writer in 1903 from the Magothy formation of New Jersey, to which it has been heretofore confined. Fragmentary leaves are, however, present in the deposits along Black Creek in South Carolina. The form is somewhat similar to species of the Dakota sandstone *Myrica aspera* Lesquereux.[1]

Occurrence.—Black Creek formation, right bank of Black Creek, 2 miles below Williamson's bridge, Florence County, (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

MYRICA ELEGANS Berry.

Plate IX, figure 4.

Myrica elegans Berry, Bull. Torrey Bot. Club, vol. 34, 1907, p. 191, Pl. XI, figs. 1–4, 6.

Description.—Leaves ovate-lanceolate in outline, variable in size, ranging from 3.2 to 9.5 centimeters in length by 1.5 to 3 centimeters in greatest width, which is midway between the apex and the base. Like the living species of Myrica the margin is variable, ranging from forms in which it is rather angularly crenate with an approach to serrate in some of the teeth, through forms in which the crenations become more and more rounded, until the extreme of variation in this direction shows relatively broad leaves with deeply scalloped subcrenate margins. Midrib straight and fairly stout. Secondaries numerous, 5 to 17 pairs, relatively stout and prominent on the lower surface of the leaf, subopposite or alternate, equidistant and parallel, branching from the midrib at angles of more than 45°, approaching 90° in some specimens. They are nearly straight and craspedodrome, running to the marginal teeth. Tertiaries usually not seen because of the coarse matrix. Some transverse veinlets are discernible, as well as curved branches from the distal part of the secondaries, which run to the subordinate teeth of the marginal scallops when these are developed. Apex pointed. Base cuneate and generally with an entire margin. Texture subcoriaceous.

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[1] Lesquereux, Leo, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, p. 66, 1892, Pl. II, fig. 11.

This species is markedly distinct from any other Cretaceous Myrica. It is very abundant in the Black Creek formation of the upper Cape Fear River in North Carolina, but has only been found at Darlington in the South Carolina area, and there in a much macerated condition. Although the resemblance is not close, *Myrica elegans* is more like *Myrica præcox*, described by Heer from the Patoot beds of Greenland, than it is like any other species with which it has been compared. The latter is a smaller leaf with a rounded apex, and the wide marginal crenations lack the crenulations of the Carolina species.

Occurrence.—Black Creek formation, near Darlington, Darlington County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Order **SALICALES.**

Family **SALICACEÆ.**

Genus **SALIX** Linné.

SALIX FLEXUOSA Newberry.

Plates VII, figures 14–16, and XI, figure 1.

Salix flexuosa Newberry, Notes on the later extinct floras of North America: Ann. Lyc. Nat. Hist. New York, vol. 9, 1868, p. 21.

Salix flexuosa Newberry, Illustrations of Cretaceous and Tertiary plants, 1878, Pl. I, fig. 4.

Salix protexfolia linearifolia Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 49, Pl. LXIV, figs. 1–3.

Salix protexfolia flexuosa Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 50, Pl. LXIV, figs. 4, 5.

Salix protexfolia flexuosa Hollick, Bull. Torrey Bot. Club, vol. 21, 1894, p. 50, Pl. CLXXIV, fig. 5.

Salix protexfolia flexuosa Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 59, Pl. IV, fig. 5a.

Salix flexuosa Berry, Ann. Rept. State Geologist, New Jersey, for 1905, 1906, p. 145.

Salix flexuosa Berry, Bull. Torrey Bot. Club, 1906, vol. 33, p. 171.

Salix protexfolia flexuosa Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 67, Pl. XLVIII, fig. 12, Pl. LII, fig. 2.

Salix protexfolia linearifolia Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 52, Pl. VIII, fig. 12.

Salix protexfolia flexuosa Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 51, Pls. VIII, figs. 5, 6a, XXXVII, fig. 8b.

Description.—Leaves narrow, linear-lanceolate in outline, equally pointed at both ends, short petioled, ranging from 5 to 10 centimeters in length and from 8 to 13 millimeters in greatest width. Margin entire. Midrib stout below, tapering above, commonly somewhat flexuous. Secondaries more or less remote, about ten alternate pairs, branching from the midrib at angles varying from 35° to 45°, camptodrome, of fine caliber, in many specimens often obsolete.

This species was described by Newberry from the Dakota sandstone in 1868. Lesquereux subsequently made it one of the varieties of his *Salix protexfolia*, although it is obviously entitled to independent specific rank. It is of rare occurrence in the Raritan formation, where it first appears in the uppermost beds at South Amboy, N. J., and is preeminently a species which characterizes the Magothy and homotaxial horizons to the southward. It is recorded in beds of Magothy age from Marthas Vineyard to the Potomac. It occurs in the Black Creek formation of North Carolina and at a large number of localities in the Tuscaloosa formation in the western part of Alabama.

In South Carolina it has been found in considerable abundance in the Middendorf arkose member of the Black Creek formation entirely across the State, and fragments which have been doubtfully identified as this species are present well toward the top of the Cretaceous on Congaree River.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; near Langley, Aiken County; right bank of Congaree River, about 25 miles below Columbia, Lexington County. (Collected by E. W. Berry, L. W. Stephenson, B. L. Miller, and M. W. Twitchell.)

Collections.—U. S. National Museum.

SALIX LESQUEREUXII Berry.

Plate VII, figures 11–13.

Salix protexfolia Lesquereux, Am. Jour. Sci., 2d ser., vol. 46, 1868, p. 94 (non Forbes).

Salix protexfolia Lesquereux, The Cretaceous flora, 1874, p. 60, Pl. V, figs. 1–4.

Salix protexfolia Lesquereux, in Cook and Smock, Report on the clay deposits of Woodbridge, South Amboy, and other places in New Jersey, 1878, p. 29.

Salix protexfolia Lesquereux, The Cretaceous and Tertiary floras, 1883, p. 42, Pls. I, figs. 14–16, and XVI, fig. 3.

Salix protexfolia Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 49.

Salix protexfolia longifolia Lesquereux, idem, 1892, p. 50, Pl. LXIV, fig. 9.

Salix protexfolia longifolia Bartsch, Bull. Lab. Nat. Hist., Univ. Iowa, vol. 3, 1896.

Proteoides daphnogenoides Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 72 (pars), Pl. XXXII, fig. 11.

Dewalquea groenlandica Newberry, idem, p. 129 (pars), Pl. XLI, fig. 12.

Salix protexfolia Newberry, idem, p. 66, Pl. XVIII, figs. 3, 4.

Salix protexfolia Kurtz, Revista Mus. La Plata, 1902, vol. 10, p. 51.

Salix protexfolia Berry, Ann. Rept. State Geologist, New Jersey, for 1905, 1906, p. 139.

Salix protexfolia Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 171, Pl. VII, fig. 2.

Salix protexfolia Berry, idem, vol. 36, 1909, p. 252.

Description.—Leaves ovate-lanceolate in outline, somewhat more acuminate above than below, variable in size, ranging from 6 to 12 centimeters in length and from 1.1 to 2.2 centimeters in greatest width, which is usually slightly below the middle. Petiole stout, much longer than in *Salix flexuosa*, the largest being 1.2 centimeters long. Midrib stout below, tapering above. Secondaries numerous, sometimes as many as twenty pairs; they branch from the midrib at angles of about 45° and are parallel and camptodrome.

This is an exceedingly variable species, as might be expected in a Salix, and Lesquereux established several varieties, of which at least one, *linearifolia*, is referable to *Salix flexuosa* Newberry. Some of Lesquereux's forms are distinguishable with difficulty from the latter, as is well shown by examination of the leaves which he figures on Plate I of his "Cretaceous and Tertiary floras." These leaves are, however, larger and somewhat more robust, of a thicker texture, and broadest near the base, from which they taper upward to an exceedingly acuminate tip. In general, *Salix lesquereuxii* is a relatively much broader, more ovate form with more numerous and easily seen secondaries and a longer petiole.

This species is an exceedingly abundant Cretaceous type in both the East and the West. In the Atlantic Coastal Plain it ranges from the base of the Raritan formation to the top of the Tuscaloosa formation and is abundant in the Magothy, Black Creek, and Tuscaloosa formations. In the West it is common in the Dakota sandstone. It is one of the forms recorded by Kurtz from the Upper Cretaceous of Argentina, indicating, if the identification is correct, a very considerable migration during the early Upper Cretaceous.

It is abundant in South Carolina in both the Middendorf member and other deposits of the Black Creek formation.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County, near Langley and Miles Hall, Aiken County; Rocky Point, Sumter County; right bank of Congaree River, about 25 miles below Columbia, Lexington County. Other deposits of the Black Creek formation near Darlington, Darlington County. (Collected by E. W. Berry, L. W. Stephenson, B. L. Miller, M. W. Twitchell, and Earle Sloan.)

Collections.—U. S. National Museum.

SALIX PSEUDOHAYEI Berry.

Plate X, figure 8.

Salix sp. Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 68, Pl. XLII, figs. 6–8.
Salix pseudohayei Berry, Bull. Torrey Bot. Club, 1909, vol. 36, p. 251.

Description.—Leaves small, relatively short and broad, ovate-lanceolate, uniformly about 3 centimeters in length by 1.1 to 1.4 centimeters in greatest width, which is about halfway between the apex and base or lower apex acuminate. Base rounded. Margin entire. Petiole short. Midrib slender and slightly curved. Secondaries fine, obscured in some specimens, five or six pairs, alternate, camptodrome, branching from the midrib at an angle of about 45° and curving upward.

This species is not uncommon in the Raritan formation of New Jersey, although Prof. Newberry fails to mention the exact localities from which he collected it. Later material has come from the lower part of the Raritan at Milltown, N. J. It has been compared with the Dakota sandstone species, *Salix hayei* Lesquereux, and with the Arctic Tertiary *Salix ræana* Heer, both of which it resembles in general appearance. The leaf from the Dakota sandstone, however, is coriaceous, with a coarse venation, blunt apex, and more narrow pointed base, and is seen to be quite different from the eastern species when careful comparisons are made.

The single specimen figured is all that represents this species in the South Carolina Cretaceous. It is in every respect identical with the type material from New Jersey.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

SALIX SLOANI sp. nov.

Plate VIII, figures 10–12.

Description.—Leaves lanceolate in outline, large and elongated, 13 centimeters or more in length by 1.6 to 3 centimeters in greatest width, which is about halfway between the apex and the base, the leaf tapering gradually and equally distad and proximad to the narrowly acute and extended apex and base. The margin is entire for a short distance below, above which it is beset with short, triangular, generally obtusely pointed, somewhat aquiline teeth, separated by rounded sinuses. Midrib stout. Secondaries very numerous, thin, approximately parallel, branching from the midrib at wide angles, 60° to 70°, at intervals of 2 to 3 millimeters, extending outward with only a slight upward curve to a point near the margin and then curving upward and extending for a greater or less distance almost parallel with the latter, giving off short tertiary branches to the marginal teeth. Tertiaries fine, exceedingly numerous, transverse, parallel at nearly right angles to the midrib.

This very striking and exceedingly distinct and characteristic species is not rare at the locality near Langley, though few complete leaves are found. It has not been detected elsewhere in the Atlantic Coastal Plain. It is much like certain modern species of Grevillea and other antipodean members of the family Proteaceæ, but may be compared with a number of existing species of Salix, as, for example, *Salix fluviatilis* Nuttall. It is believed to be referable with certainty to this genus and is one of the most ancient forms known which show decisive characters identical with those of modern willow leaves. The most nearly related fossil species, one perfectly distinct, however, is *Salix eutawensis* Berry,[1] which has been recorded from the Black Creek formation in North Carolina and from the Eutaw formation in western Georgia.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley and Miles Hall, Aiken County. (Collected by L. W. Stephenson, E. W. Berry, and Earle Sloan.)

Collections.—U. S. National Museum.

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[1] Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 193, Pl. XXII.

Order **FAGALES**.

Family **FAGACEÆ**.

Genus **QUERCUS** Linné.

QUERCUS SUMTERENSIS sp. nov.

Plate X, figures 9 and 10.

Description.—Leaves large, linear, acuminate, coriaceous, entire, with a broadly cuneate base. Length about 15 to 16 centimeters. Greatest width 3 centimeters. Petiole short and stout, midrib stout. Secondaries thin, branching from the midrib at angles of 45° or more, taking a rather straight course almost to the margin and then turning sharply upward. Tertiaries obsolete, as are also the secondaries in some specimens.

This species is clearly referable to the willow or laurel oaks and is markedly distinct from any species hitherto described, although it resembles in general outline some of the lanceolate Cretaceous species of Ficus. It is not uncommon at the Rocky Point locality, to which it is thus far confined. It is not unlike some of the leaves of the modern *Quercus rudkini*, a hybrid of *Quercus marylandica* and *phellos*.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. F. Ward and L. C. Glenn.)

Collections.—U. S. National Museum.

QUERCUS PSEUDOWESTFALICA sp. nov.

Plate IX, figure 5.

Description.—Leaves of medium size, relatively small for this genus, ovate in general outline, with an acuminate apex and a cuneate base. Texture coriaceous. Length about 9.5 centimeters. Greatest width about 4 centimeters near the middle of the leaf. Margin with large serrate teeth separated by broadly rounded sinuses. Midrib stout. Secondaries thin, approximately parallel, about seven subopposite pairs, branching from the midrib at angles of about 45°, slightly curved, craspedodrome, ending in the marginal teeth, of which there is one to each secondary. Petiole not preserved.

This species evidently belongs to the group of the chestnut oaks, not differing materially from certain leaves which may be collected from the existing *Quercus michauxii*, *prinus*, or *prinoides* of eastern North America. Among fossil species it is very similar to some of the varieties of *Quercus westfalica* figured by Hosius and von der Marck [1] from the Senonian of Westphalia, and it is especially close to one of the Bohemian leaves which Velenovsky [2] refers to this species. Heer [3] records this same species from the Atane beds of Greenland, but his specimens are too fragmentary for any great certainty of identification. Another leaf which is very similar is one from Kieslingswalde in Silesia, which Velenovsky identifies with his *Quercus pseudodrymeja*,[4] although it is more probably referable to *Quercus westfalica*.[5] No Atlantic Coastal Plain species is closely similar to *Quercus pseudowestfalica*, although *Quercus eoprinoides* Berry [6] from the Magothy formation in New Jersey is remotely related to it, as is also *Quercus raritanensis* Berry [7] from the Raritan formation of that State.

A form which is closely related to the Carolina species, however, is *Quercus dakotensis* Lesquereux.[8] It is of about the same size and outline, but differs in having less prominent teeth and in the details of its tertiary venation.

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[1] Palæontographica, vol. 26, 1880, p. 161, Pls. XXIX, figs. 52–63; XXX, figs. 64–75.

[2] Velenovsky, J., Die Flora der böhmischen Kreideformation, pt. 2, 1883, p. 17, Pl. II, fig. 23.

[3] Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 67, Pl. XV, figs. 5–7.

[4] Op. cit., figs. 21, 22.

[5] Op. cit., pt. 4, 1885, p. 13, Pl. VII, fig. 10.

[6] Berry, E. W., Bull. Torrey Bot. Club, vol. 31, 1904, p. 74, Pl. IV, fig. 11.

[7] Idem, vol. 36, 1909, p. 249.

[8] Lesquereux, Leo, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 56, Pl. VII, fig. 4.

Quercus pseudowestfalica has been found in only the Middendorf member of the Black Creek formation of South Carolina. It has also been doubtfully determined from the Black Creek formation at Court House Bluff in North Carolina.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; Rocky Point, Sumter County, and Miles Mill, Aiken County. (Collected by E. W. Berry, L. W. Stephenson, and Earle Sloan.)

Collections.—U. S. National Museum.

Order URTICALES.

Family ULMACEÆ.

Genus MOMISIA F. G. Dietrich.

MOMISIA CAROLINENSIS sp. nov.

Plate XII, figure 5.

Description.—Leaves entire below, more or less dentately toothed apically, ovate in outline, 6 or 7 centimeters in length by 2.5 centimeters in greatest width. Apex narrowed and pointed. Base cuneate, not quite equilateral, finally decurrent on the stout petiole, which is short, 6 or 7 millimeters in length. Midrib stout below, becoming thin distad. Basal secondaries, constituting the lateral primaries, subopposite, branching from a point at or near the base of the midrib at acute angles, long, nearly straight, ascending, camptodrome. Upper secondaries remote, thin, camptodrome.

This species of a quasi triple-veined leaf seems allied to the existing species of Momisia, of which no fossil forms are known except a single species from the Eocene of Georgia described recently by the writer. Leaves of this character are commonly referred to the genus Cinnamomum or at least to the Lauraceæ, but the botanical affinity of this form seems to be with certain tropical Ulmaceæ. The existing species of Momisia number a score or more forms of the American tropics. They are closely related to Celtis and are even made a subgenus of Celtis by Engler. These leaves differ from the described species of Cinnamomum and its allies in their toothed margins and in the character of their tertiary venation, and may be considered the Cretaceous representative of the Claiborne species of Momisia.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Family ARTOCARPACEÆ.

Genus FICUS Linné.

FICUS ATAVINA Heer.

Plate X, figure 11.

Ficus protogæa Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 108, Pls. XXIX, fig. 2b, and XXX, figs. 1–8. (von Ettinsghausen.)

Ficus protogæa Schenk, Palæontographica, vol. 23, 1875, p. 169, Pl. XXIX, fig. 12.

Ficus atavina Heer, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 69, Pls. XI, figs. 5b, 7b, 8b; XVII, fig. 8b; XIX, fig. 1b; and XX, figs. 1, 2.

Ficus atavina Heer, idem, vol. 7, 1883, p. 26.

Ficus atavina? Lesquereux, Proc. U. S. Nat. Mus., vol. 10, 1887, p. 40.

Ficus protogæa Hollick, Bull. Torrey Bot. Club, vol. 21, 1894, p. 51, Pl. CLXXV, fig. 4.

Ficus atavina Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 75, Pls. I, figs. 8, 9, and III, fig. 6.

Ficus atavina Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 58, Pl. X, figs. 5, 6 (not fig. 4, which is referable to *Juglans elongata*).

Description.—Leaves entire, broadly oblong-lanceolate in outline, large in size, the South Carolina leaves measuring about 20 centimeters in length by 3.5 centimeters in greatest width, which is about halfway between the apex and the base. Apex and base equally acute. Midrib very stout. Texture coriaceous. Secondaries numerous, parallel, branching from the midrib at angles of more than 45°, camptodrome. Tertiaries rarely seen, forming small four or five sided areoles.

This large fig leaf stands about midway between *Ficus krausiana* and *Ficus crassipes*, and may possibly represent the somewhat narrower, more elongated leaves of the former species. It was described originally from Greenland as *Ficus protogæa* Heer, a preoccupied name, and was subsequently renamed by its describer. It has been recorded by Hollick from Marthas Vineyard and Long Island, from what are apparently Magothy deposits, and by the writer from the Magothy formation of New Jersey. Lesquereux recorded it from the far West (Utah), but the writer has not seen his material and queries the citation, for the species appears to be confined in this hemisphere, at least, to eastern North America. The range was possibly extended to Europe, because Schenk identifies it in the Gosau beds of the northern Tyrol. It has not heretofore been discovered in Alabama or in deposits of the southern Atlantic Coastal Plain.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County; near Middendorf, Chesterfield County. (Collected by L. F. Ward, L. C. Glenn, L. W. Stephenson, and E. W. Berry.)

Collections.—U. S. National Museum.

FICUS CELTIFOLIUS sp. nov

Plate XII, figure 4.

Description.—Leaves small, entire, elliptical-ovate in outline with an obtusely pointed apex and a broadly rounded base. Petiole short, about 0.6 centimeter in length, relatively stout. Midrib stout. Secondaries stout, remote, three or four pairs, the lower pair opposite, diverting from the midrib just below its base and functioning as lateral primaries, the balance alternate. All branch from the midrib at angles of about 45° and are camptodrome some distance from the margin. Tertiaries distinct, the inner transverse, the peripheral camptodrome in uniform broad arches.

This species, which is obviously unlike any previously described Ficus, is the sole representative of the palmately veined figs found in South Carolina, although the somewhat similar species *Ficus woolsoni* Newberry and *Ficus ovatifolia* Berry occur in either the Black Creek formation of North Carolina or the Tuscaloosa formation of Alabama. It is especially characterized by the prominence of its secondary and tertiary venation, and is very similar to certain modern species of Celtis with entire margins, as, for example, *Celtis crassifolia* Lamarck, and *Celtis reticulata* Torrey. It is also similar to a number of Tertiary species of Ficus and not unlike a very much larger undescribed species of Ficus present in clays of the Tuscaloosa formation of western Alabama.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

FICUS CRASSIPES (Heer) Heer.

Plates X, figure 12, and XII, figures 8–10.

This species is described in the section of this report dealing with the Upper Cretaceous flora of Georgia, pages 110–111. It is common in South Carolina, especially at the Rocky Point locality, from which the figured specimens were collected. It is especially characteristic of the post-Raritan and pre-Montana horizons of eastern North America.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; near Langley, Aiken County; Rocky Point, Sumter County; right bank of Congaree River about 25 miles below Columbia, Lexington County. (Collected by E. W. Berry, L. F. Ward, L. C. Glenn, B. L. Miller, and M. W. Twitchell.)

Collections.—U. S. National Museum.

FICUS KRAUSIANA Heer.

Plate XI, figures 4–7.

Ficus krausiana Heer, Neue Denkschr. Schw. Gesell., vol. 23, 1869, p. 15, Pl. V, figs. 3–6.
Ficus beckwithii Lesquereux, The Cretaceous and Tertiary floras, 1883, p. 46, Pls. XVI, fig. 5, and XVII, figs. 3 and 4.
Ficus suspecta Velenovsky, Die Flora der böhmischen Kreideformation, pt. 4, 1885, p. 10, Pl. V, figs. 6, 9.
Ficus atavina Heer? Hollick, Trans. New York Acad. Sci., vol. 2, 1892, p. 103, Pl. IV, figs. 4, 6.
Ficus krausiana, Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 81, Pl. I, fig. 5.
Ficus beckwithii Lesquereux, idem., vol. 17, 1892, p. 80.
Ficus krausiana Hollick, Bull. Geol. Soc. America, vol. 7, 1895, p. 13.
Ficus krausiana Hollick, Annals New York Acad. Sci., vol 11, 1898, p. 59, Pl. III, fig. 1.
Ficus krausiana Berry, Bull. Torrey Bot. Club, 1906, vol. 33, p. 172.
Ficus krausiana Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 58, Pls. IX, fig. 9, and X, figs. 1–3.

Description.—The following is Heer's description of this species, written in 1869:

> F. foliis lanceolatis, integerrimus, utrinque attenuatis, nervo medio valido, nervis secundis numerosis, camptodromis, subtillissimis.

Leaves of large size, ovate lanceolate in outline, broadest at or below the middle. Apex and base acutely pointed, the apex often extended and attenuated. Petiole and midrib stout. Secondaries regular, open, thin, ascending, camptodrome, branching from the midrib at angles of 45° or more. Texture coriaceous or subcoriaceous. Length about 17 centimeters. Greatest width about 4 centimeters.

This species was described by Heer from Moletein in Moravia (Cenomanian), and it has been subsequently identified from a large number of American localities. In the West it occurs in the Dakota sandstone of Kansas and Colorado; in the East it is common from Marthas Vineyard and Block Island to Alabama and is present between these limits in Maryland, North Carolina, and South Carolina. These occurrences are all in beds of the Magothy or homotaxial formations, the only uncertain occurrence being that at Tottenville, Staten Island, where the morainic material containing this species may possibly have been derived from the Raritan, although this is considered doubtful.

Associated with this species at the type locality in Moravia are similar leaves which were described by Prof. Heer as a different species, *Ficus mohliana.* These are somewhat larger with a more sparse secondary venation. It seems probable that these merely represent the somewhat larger leaves of *Ficus krausiana,* but they are not united with it in view of the lack of positive evidence, because *Ficus mohliana* has priority and this would involve the change of name of this well-known type and horizon marker. In both North and South Carolina fruits are found associated with this species, but whether they are related to it or to some of the other rather numerous species of Ficus which occur at the same localities can not be determined.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County (?); Rocky Point, Sumter County; right bank of Congaree River, about 25 miles below Columbia, Lexington County (?). Other deposits of the Black Creek formation, Black Creek, Florence County. (Collected by L. F. Ward, L. C. Glenn, E. W. Berry, L. W. Stephenson, and M. W. Twitchell.)

Collections.—U. S. National Museum.

FICUS STEPHENSONI Berry.

Plate XII, figures 1–3.

Ficus stephensoni Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 194, Pl. XXIII, figs. 2, 3.

Description.—Leaves variable in size, ranging from 6 to 18 centimeters in length and from 2.3 to 6.4 centimeters in greatest width, broadly lanceolate-ovate, tapering equally from the middle toward both ends but more fully rounded at the base and more slender toward the tip, especially in the smaller leaves. Midrib broad. Secondaries very slender, leaving the midrib at wide angles which become as great as 90° in some of the larger specimens, very numerous, 2 to 4 millimeters apart, parallel, almost straight to the marginal vein, which is well marked and about 1 millimeter distant from the margin, with which it is parallel. Veinlets largely at right angles to the secondaries and not especially well shown. Petiole stout.

This is an exceedingly well-marked species of Ficus and is very close to various existing species in form and venation characters, as is well shown by a comparison with the leaves of *Ficus elastica* Roxburg. It is probable, however, that the texture of the fossil species was less coriaceous, for all the larger leaves are considerably macerated.

It is believed that the larger forms represent the normal size of the leaves in this species and that the smaller leaves, which occur only in material from South Carolina, represent abortive leaves which fell before reaching maturity, as is so common in the modern allied species.

Some authors refer leaves of this type to the genus Eucalyptus, with which genus the venation has much in common. In point of size the Carolina leaves are comparable with those of such a species as *Eucalyptus latifolia* Hollick from Glen Cove, Long Island, but the secondaries are less regular and only about half as numerous in the latter species, and there seems to be little doubt of the propriety of referring the present species to the genus Ficus.

It is very similar to a variety of closely related Upper Cretaceous species of Ficus of the type of the existing *Ficus elastica* Roxburg and its allies, commonly cultivated as ornamental shrubs and trees under the name of "rubber plants." The comparable fossil forms include *Ficus glascoeana* Lesquereux,[1] with which there is a possibility that the present species may be identical, as it is very similar in outline and venation, except that the figures of the Kansas leaves (types 478 and 532a, Museum of Comparative Zoology) do not show any marginal vein, although Lesquereux mentions one in his description. The latter species has been detected southward along the western shore of the Mississippi embayment in the Woodbine sand of Texas and is of a more coriaceous texture, with more obtuse tip, and with the secondaries joining the midrib at an angle of 60°. Another very similar species is *Ficus atavina* Heer,[2] which ranges from the Atane and Patoot beds of western Greenland southward along the Atlantic Coastal Plain to Marthas Vineyard, Glen Cove, Long Island, and Cliffwood, N. J. All the occurrences are probably of Magothy age.

The North Carolina leaf has full-rounded basal margins, which are rather straight in *Ficus atavina;* its secondaries, which are twice as numerous as in *Ficus atavina,* are less ascending. The marginal vein is also closer to the margin. Another species, perhaps identical with the previous one, is *Ficus peruni* Velenovsky,[3] from the Cretaceous of Bohemia, which differs from the North Carolina leaf in the same respects in which *Ficus atavina* Heer differs. Velenovsky points out the great similarity between *Ficus peruni* and *Eucalyptus geinitzii* Heer, a similarity which is more striking in the forms he has referred to this species of Eucalyptus than in the leaves usually so identified by other paleobotanists.

Ficus stephensoni was recently described by the writer[4] from material collected in the Black Creek formation at Court House Bluff on Cape Fear River in North Carolina. It is found to be equally abundant in clays of the Middendorf member of the Black Creek formation across the State of South Carolina, but has not been certainly detected elsewhere in the Atlantic Coastal Plain, though doubtful remains which may represent this species are present in the collections from clays of the Tuscaloosa formation of western Alabama.

Occurrence.—Middendorf arkose member of Black Creek formation, Middendorf, Chesterfield County; near Langley, Aiken County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

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[1] Lesquereux, Leo, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 76, Pl. XIII, figs. 1, 2.

[2] Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 108, Pls. XXIX, fig. 2b, and XXX, figs. 1-8.

[3] Die Flora der böhmischen Kreideformation, pt. 3, 1884, p. 16 (41), Pl. IV (12), figs. 1-3. Compare his fig. 2 with Berry, Bull. Torrey Bot. Club, vol. 31, 1904, Pl. III, fig. 6.

[4] Loc. cit.

Order **PROTEALES.**

Family **PROTEACEÆ.**

Genus **PROTEOIDES** Heer.

PROTEOIDES LANCIFOLIUS Heer.

Plate X, figure 1.

Proteoides lancifolius Heer, Zur Kreideflora von Quedlinburg, 1871, p. 12, Pl. III, figs. 5, 6.
Proteoides lancifolius Lesquereux, The Cretaceous and Tertiary floras, 1883, p. 50.
Proteoides lancifolius Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 90, Pls. XV, fig. 5, and I, fig. 8.

Description.—Leaves entire, lanceolate, commonly falcate in outline, with a narrowed attenuated apex and a narrowed decurrent base, about 10 centimeters in length by 1.4 centimeters in greatest width, which is in the basal half of the leaf. Petiole stout. Midrib stout below, rapidly narrowing upward. Secondaries very numerous, approximately parallel, many obsolete, branching from the midrib at acute angles of less than 45°. These are connected by branches or tertiaries in the irregular manner characteristic of the venation of existing Proteaceæ. Texture coriaceous.

This species was origially described from the Cretaceous of Blankenburg, Saxony, by Heer. Lesquereux recorded it from the Dakota sandstone and it is not uncommon in the South Carolina Cretaceous, the latter remains being identical with the Dakota sandstone specimens and identical with the type material except that in some of the leaves of the South Carolina specimens the upper secondaries are depicted as open and camptodrome, subtending a wider angle with the midrib, a character different from that shown in the lower secondaries of the same specimens. All the observed characters are identical with those of various existing genera of the Proteaceæ, as, for example, the genus Protea. The present species does not differ to any extent from the Dakota sandstone species, *Proteoides acuta* Heer and *Proteoides grevilliæformis* Heer, the latter the type of the genus. The genus Proteoides does not contain many described species and is confined to pre-Montana deposits in North America, although it ranges upward into the Senonian of Europe.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; Rocky Point, Sumter County. Other deposits of the Black Creek formation, near Darlington, Darlington County. (Collected by E. W. Berry, L. C. Glenn, and L. W. Stephenson.)

Collections.—U. S. National Museum.

PROTEOIDES PARVULA sp. nov.

Plate X, figure 5.

Description.—Leaves of small size, lanceolate in outline, entire, somewhat falcate, with equally acute apex and base, 2 centimeters in length by 4.5 millimeters in greatest width, which is about halfway between the apex and the base. Midrib thin, somewhat flexuous. Secondaries fine, immersed, and mostly obsolete, numerous, ascending, irregularly anastomosing.

This species is one of the smallest which has been referred to this genus, and except for its size is very similar to *Proteoides lancifolius* Heer, which occurs at the same locality—in fact, it may simply be a juvenile form of the latter. This can only be determined by a larger amount of comparative material than is available at the present time.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Order **RANALES.**

Family **RANUNCULACEÆ** (?).

Genus **DEWALQUEA** Saporta and Marion.

DEWALQUEA SMITHI Berry.

Plate VIII, figures 3–9.

Dewalquea smithi Berry, Torreya, vol. 10, 1910, p. 36, fig. 1.

Description.—Leaves palmately decompound, the petiole dividing into three principal branches, the angle of divergence varying from 20° to 60° and the two lateral branches forking at an acute angle 1 to 2 centimeters above their base. The middle leaflet is lanceolate in outline, being widest in its central part and tapering almost equally to the acute apex and base. Length 7.5 to 16 centimeters. Greatest width 2 to 4 centimeters. Margin entire or serrate, usually entire below and serrate in the apical three-fourths, some specimens having large aquiline-serrate teeth. Midrib stout. Secondaries regular, subopposite, parallel; about 20 pairs, branching from the midrib at angles varying from 45° to 70°, generally about 50°, curving upward and running to the marginal teeth or camptodrome. The base of the leaflet extends downward within 2 or 3 millimeters of the forks of the petiole. Lateral leaflets more or less inequilateral, usually somewhat smaller than the middle leaflet. The internal lateral leaflet is lanceolate, the outer lamina starting at or very near the point where the lateral branch of the petiole forks. The inner lamina, however, extends downward almost to the base of the lateral branch, making the base markedly inequilateral. In general outline and in marginal and venation characters it is identical with the middle leaflet. The outer lateral leaflet is also somewhat inequilateral, but less so than the internal lateral leaflet, the internal lamina starting at or near the fork and its outer lamina extending more or less below the fork. Marginal and venation characters as in the outer leaflets. This handsome species, of which a restoration is shown in figure 1, is abundantly represented at the locality near Langley, mostly by terminal

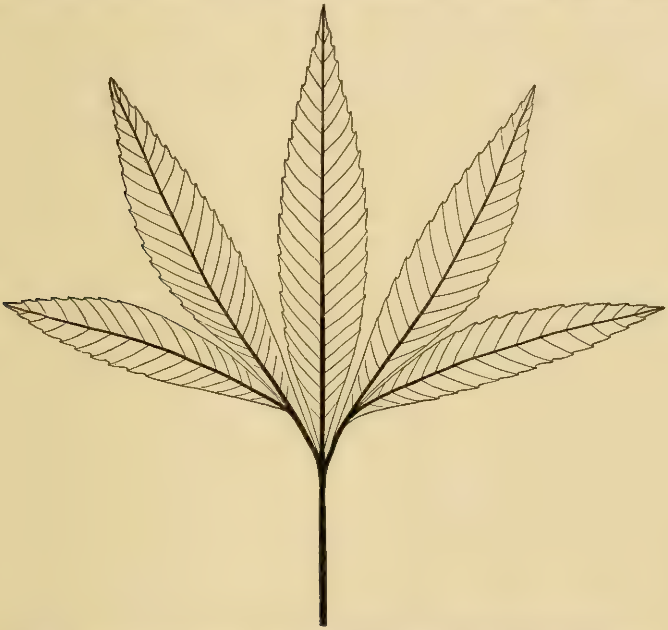

FIGURE 1. Restoration of *Dewalquea smithi* Berry, from the Tuscaloosa formation of western Alabama.

leaflets, a number of which are reproduced in Plate VIII, figures 3–9. It is common in the Tuscaloosa formation at Whites Bluff, on the right bank of Warrior River 309 miles above Mobile, Ala., a small collection of fossil plants from this outcrop containing no less than 27 specimens of this form. Several of these were complete and were sketched at the time they were collected, which proved fortunate, as the extremely arenaceous matrix did not withstand shipment very well. The museum material, though considerably broken, shows several entire detached leaflets and three or four basal parts of the leaf showing the mode of division of the petiole.

The genus Dewalquea was founded by Saporta and Marion in 1874 [1] upon remains from the Senonian of Westphalia communicated by Debey and named by him in manuscript Araliophyllum, and on additional remains collected by those authors from the Paleocene of Gelinden, Belgium (marnes heersiennes, étage Thanétien). Three species were enumerated, *Dewalquea haldemiana* and *Dewalquea aquisgranensis* from the Westphalian Senonian and *Dewalquea gelindenensis* from the basal Eocene. In the past 35 years several additional species have been referred to this genus, including another species from the German Senonian, *Dewalquea insignis*, described by Hosius and Von der Marck; [2] two species from the Cenomanian of Bohemia, *Dewalquea coriacea* and *Dewalquea pentaphylla*, described by Velenovsky; [3] two American species from the Dakota sandstone, *Dewalquea dakotensis* and *Dewalquea primordialis*, described by Lesquereux,[4] both of which are fragmentary and of uncertain relationship; a species from the Raritan formation of New Jersey, *Dewalquea trifoliata*, described by Newberry; [5] and a species described by Heer [6] from Greenland, *Dewalquea groenlandica*, and subsequently recorded from Staten Island, New Jersey, North Carolina, and Alabama.

Hosius and Von der Marck [7] record the Eocene species from the Senonian of Westphalia, but the remains are not of this species, being fragments of *Dewalquea haldemiana*, which is common at that horizon. The European species *Dewalquea insignis* is recorded by Heer [8] both from the Atane and Patoot beds of Greenland and by Hollick [9] from the Cretaceous of Staten Island, but both of these determinations are based upon fragments of single leaves and are, in the writer's judgment, entirely untrustworthy. Attention should also be called to the possibility of *Celastrus arctica* Heer [10] representing the leaflets of a Dewalquea. This species was described from the Patoot beds of Greenland, where it is sparsely represented. It is abundant, however, in the upper part of the Raritan formation of New Jersey, but of some scores of specimens examined by the writer all were detached and failed to show their habit of growth.

The botanic relationship of Dewalquea has always remained obscure and no better discussion of it is extant than that given by Saporta and Marion,[11] who, after comparing these leaves with those of Ampelopsis, Arisæma, Anthurium (Araceæ), and other genera, arrive at the conclusion that they are prototypes of the tribe Helleboreæ of the Ranunculaceæ.

The present species is markedly distinct from the American species of Dewalquea previously described, all of which were apparently tripartite. Among the European species it is quite similar to the Senonian species *Dewalquea insignis* Hosius and von der Marck, which is, however, entirely distinct. It is also similar to *Dewalquea coriacea* and *Dewalquea pentaphylla* described by Velenovsky from the Cenomanian of Bohemia.

As previously mentioned, this species shows both entire and serrated forms. It is remarkable that where this genus has been found in any abundance, two species are usually described, one entire and one with toothed margins. Thus in Germany *Dewalquea haldemiana* is entire, whereas *Dewalquea insignis* is toothed, and probably both are the leaves of the same plant. In Bohemia *Dewalquea pentaphylla* is entire and *Dewalquea coriacea* is toothed. As for the Alabama plant, it is believed that the entire and serrate leaves are specifically identical, for the material shows a great many gradations in the size of the teeth and great variability regarding the proportion which the entire part of the margin bears to the toothed part on single leaflets.

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[1] Saporta, G. de, and Marion, A. F., Essai sur l état de la végétation à l'époque des marnes heersiennes de Gelinden: Mém. cour. et des Sav. étrang. Acad. roy. Belgique, vol. 37, p. 55. 1874.

[2] Hosius and Von der Marck, Palæontographica, vol. 26, 1880, p. 172, Pl. XXXII, figs. 111–113; XXXIII, fig. 109; XXXIV, fig. 110; and XXXV, fig. 123.

[3] Die Flora der böhmischen Kreideformation, pt. 3, 1884, pp. 11, 14, Pls. I, figs. 1–9; II, fig. 2; and VIII, figs. 11, 12.

[4] The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 211, Pl. LIX, figs. 5, 6. Geol. and Nat. Hist. Survey Minnesota, vol. 3, 1893, p. 18, Pl. A, fig. 10.

[5] Newberry, J. S., The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 129, Pl. XXII, figs. 4–7.

[6] Heer, Oswald, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 87, Pls. XXIX, figs. 18, 19; XLII, figs. 5, 6; XLIV, fig. 11.

[7] Op. cit., p. 50.

[8] Op. cit., vol. 6, Abth. 2, 1882, p. 86, Pls. XXV, fig. 7; XXXIII, figs. 14–16; idem, vol. 7, 1883, p. 37, Pls. LVIII, fig. 3; LXII, fig. 7.

[9] The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 106, Pl. VIII, fig. 24.

[10] Op. cit., vol. 7, 1883, p. 40, Pl. LXI, figs. 5d, 5e.

[11] Op. cit., pp. 55–61.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley and Miles Mill, Aiken County. (Collected by L. W. Stephenson, E. W. Berry, and Earle Sloan.)

Collections.—U. S. National Museum.

Family MAGNOLIACEÆ.

Genus MAGNOLIA Linné.

MAGNOLIA CAPELLINII Heer (?).

Plate X, figure 3.

This species, which is confined to the Middendorf arkose member of the Black Creek formation in South Carolina, is described in the section of this report dealing with the Upper Cretaceous flora of Georgia, pages 112–113.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; Rocky Point, Sumter County. (Collected by L. C. Glenn, L. W. Stephenson, and E. W. Berry.)

Collection.—U. S. National Museum.

MAGNOLIA NEWBERRYI Berry (?).

Magnolia longifolia Hollick, Trans. New York Acad. Sci., vol. 12, 1892, p. 36, Pl. III, fig. 9.
Magnolia longifolia Smith, On the geology of the Coastal Plain of Alabama, 1894, p. 348.
Magnolia longifolia Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 422, Pl. XXXVII, fig. 3.
Magnolia longifolia Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 66, Pl. XX, figs. 2, 3 (non Sweet, 1826).
Magnolia longifolia Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 76, Pls. LV, figs. 3 and 5, and LVI, figs. 1–4.
Magnolia newberryi Berry, Bull. Torrey Club, vol. 34, 1907, p. 195, Pl. XIII, fig. 6.

Description.—Leaves mostly of large size, ovate to oblong in outline, about 20 centimeters in length by 9 to 10 centimeters in width, broadest toward the base. Apex subacute or obtuse. Base varying from obtusely rounded, almost truncate, to somewhat cuneate. Petiole and midrib stout. Secondaries comparatively thin and open, about 12 pairs, camptodrome. Tertiaries forming four, five, or six sided areoles, quite prominent in some specimens.

This is the largest magnolia of the Raritan formation, the leaves of which are said by Newberry to reach a length of 30 centimeters or more. It is common at the Woodbridge locality and has also been reported from Staten Island and Marthas Vineyard, from the Tuscaloosa formation in Alabama, and from the Black Creek formation in North Carolina. In a general way it resembles an immense leaf of *Magnolia woodbridgensis*, and it also approaches somewhat *Magnolia longipes*, but the petiole is only about one-third the length that it has in the latter species. Its occurrence in the South Carolina Cretaceous is based upon doubtfully determined material from the locality near Darlington, but it must almost certainly have been a member of the South Carolina flora, for it has been detected in homotaxial deposits both north and south of this area. (Collected by L. W. Stephenson.)

Occurrence.—Black Creek formation, near Darlington, Darlington County.

Collections.—U. S. National Museum.

MAGNOLIA OBTUSATA Heer.

Magnolia capellinii Heer, Flora Fossilis Arctica, vol. 3, Abth. 2, 1874, Pl. XXXIII, fig. 4 (non other citations of this species).
Magnolia obtusata Heer, idem, vol. 6, Abth. 2, 1882, p. 90, Pls. XV, fig. 12, and XXI, fig. 3.
Magnolia obtusata Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 201, Pl. LX, figs. 5, 6.
Magnolia obtusata Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 76, Pl. XLVII, fig. 4.
Magnolia obtusata Berry, idem, vol. 37, 1910, p. 23.

Description.—Leaves of variable size, oblong-ovate or obovate in outline, entire, with a broadly rounded apex and a narrowed cuneate base, ranging from 7 to 14 centimeters in length by 2.4 to 7 centimeters in greatest width, which is above the middle. Petiole and midrib stout. Secondaries few in number, ascending, curved, camptodrome. Texture coriaceous.

This species was described from the Atane beds of Greenland by Heer, and was based upon rather fragmentary material. Subsequently Lesquereux recorded some fine specimens from the Dakota sandstone of Kansas. It is present in the Magothy formation from New Jersey to Maryland and is also a member of the Tuscaloosa flora in western Alabama. The South Carolina specimens are few in number and come from but a single locality.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

MAGNOLIA TENUIFOLIA Lesquereux (?).

Plate IX, figures 2 and 3.

Magnolia tenuifolia Lesquereux, Am Jour. Sci., 2d ser., vol. 46, 1868, p. 100.
Magnolia tenuifolia Lesquereux, The Cretaceous flora, 1874, p. 92, Pl. XXI, fig. 1.
Magnolia tenuifolia Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 198, Pl. XXIV, fig. 1.
Magnolia tenuifolia Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 77, Pl. XLVII, fig. 10.
Magnolia tenuifolia Hollick, idem, vol. 3, 1904, p. 413, Pl. LXXIII, fig. 2.
Magnolia tenuifolia Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 76, Pl. I, fig. 7.
Magnolia tenuifolia Berry, idem, vol. 33, 1906, p. 174, Pl. VII, fig. 1.
Magnolia tenuifolia Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 64, Pls. XVII, fig. 1; XVIII, figs. 4, 5.

Description.—Leaves large, entire, oblong-ovate in outline, with a very stout petiole and midrib. Length, about 20 centimeters. Greatest width, which is about halfway between the apex and the base, about 8 centimeters. Apex bluntly pointed. Base cuneate, pointed. Secondaries open, approximately parallel, inequidistant, camptodrome.

The presence of this species in South Carolina Cretaceous is based upon the doubtfully determined fragments figured. The leaf in life was such a large one that most of the occurrences are based upon mere fragments. It was described originally from the Dakota sandstone and has subsequently been recorded from the Magothy formation on Marthas Vineyard and Long Island and in New Jersey and Delaware.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Genus **ILLICIUM** Linné.

ILLICIUM WATEREENSIS sp. nov.

Plate XIV, figure 8.

Description.—Leaves entire, lanceolate in outline, with the apex and the base acutely and equally pointed. Length about 9.5 centimeters. Greatest width 1.9 centimeters, in the middle part of the leaf. Midrib narrow but prominent. Secondaries numerous, parallel, branching from the midrib at angles of about 45°, camptodrome.

This species may be compared with a variety of described species in unrelated genera, as, for example, Nyssa, Daphne, Apocynum, Andromeda, and various lauraceous genera, but it is believed to have more in common with the Ranalian genus Illicium, in which only one other Cretaceous species, *Illicium deletum* Velenovsky,[1] from the Cenomanian of Bohemia, is known. The latter is very similar to the South Carolina leaf, differing merely in having fewer secondaries and more open secondary venation. A number of Tertiary species of Illicium are known, and the modern forms, which are seven or eight in number, inhabit the warmer parts of eastern North America and eastern Asia.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order **ROSALES.**

Family **HAMAMELIDACEÆ.**

Genus **HAMAMELITES** Saporta.

HAMAMELITES? CORDATUS Lesquereux.

Plate X, figure 2.

Hamamelites? cordatus Lesquereux, The Cretaceous and Tertiary floras, 1883, p. 71, Pl. IV, fig. 3.
Hamamelites? cordatus Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 139.

Description.—Leaves large, elliptical in outline. Length about 10 centimeters. Greatest width 6 to 7 centimeters; near the middle part of the leaf. Apex unknown. Base cordate. Margin undulate to dentate or serrate with shallow teeth. Midrib stout. Secondaries stout, numerous, approximately parallel, branching from the midrib at angles of 45° or more, nearly straight, at right angles to the secondaries. Texture coriaceous.

The genus Hamamelites was founded by Saporta in 1865 upon foreign early Tertiary material, and to it Lesquereux referred five species from the Dakota sandstone, which exhibited a combination of the characters of Hamamelis, Alnus, Viburnum, and other genera. Subsequently one of these was referred to Quercus. All were founded upon rather sparse material, particularly *Hamamelites? cordatus.* Its occurrence in South Carolina is based upon the single imperfect specimen figured, which is very similar to the figured type from the West. It shows part of the margin, the characteristic venation, and half of the typical cordate base. That Hamamelis-like forms were present at this time is shown by the presence of wood of this type described by Lignier in 1907 as Hamamelidoxylon from the Cenomanian of France.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by L. C. Glenn.)

Collections.—U. S. National Museum.

Family **MIMOSACEÆ.**

Genus **ACACIAPHYLLITES** gen. nov.

ACACIAPHYLLITES GREVILLEOIDES sp. nov.

Plate IX, figures 9 and 10.

Description.—Leaves or leaflets of small size, entire, oblong-elliptical in outline, about 2 centimeters in length by 0.5 to 0.65 centimeters in greatest width, which is at the middle part of the leaf. Apex and base equally rounded. Petiole very short and relatively stout, about 1.5 millimeters in length. Midrib thin, very much attenuated distad. Secondaries fine, numerous, approximately parallel, branching from the midrib at acute angles; long, ascending, apparently camptodrome, connected at irregular intervals by cross branchlets of the same caliber.

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[1] Velenovsky, J., Die Flora der böhmischen Kreideformation, pt. 3, 1884, p. 4, Pl. III, fig. 5.

This species is believed to show undoubted characters which ally it with the genus Acacia and is certainly referable to the families Mimosaceæ or Cæsalpiniaceæ, although suggesting the family Proteaceæ. It is totally unlike any known fossil American species but resembles certain of the Bohemian Cretaceous leaves referred by Velenovsky[1] to Grevillea or Grevilleophyllum, although, as has been said, it is here considered leguminous.

These small leaves are not uncommon at the locality near Middendorf, to which they are confined. Their small size has enabled complete specimens to be preserved, and though they are thin they appear to have had a resistant epidermis of thick-walled cells, greatly resembling a number of typical existing acacias.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Genus **CÆSALPINIA** Linné.

CÆSALPINIA MIDDENDORFENSIS sp. nov.

Plate X, figure 7.

Description.—Leaves compound. Leaflets entire, elliptical in outline, with a broadly rounded apex and a slightly broader, rounded, markedly inequilateral base, 1.5 centimeters in length by 0.9 centimeter in greatest width, which is at the middle or below. Midrib slender and curved in the single complete leaflet collected. Secondaries few and thin, four or five pairs, branching from the midrib at a wide angle, more than 45°, camptodrome.

This is a well-marked species, clearly referable to some member of the Cæsalpiniaceæ with compound leaves, usage sanctioning the reference of leaflets of this sort to the genus Cæsalpinia, with the leaflets of which they agree closely. Only two other Cretaceous species are known, both from the Raritan formation in New Jersey. With the smaller of these, *Cæsalpinia cookiana* Hollick,[2] the South Carolina form is closely comparable, but it differs in its more elongate inequilateral outline and more numerous secondaries.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Genus **LEGUMINOSITES** Bowerbank.

LEGUMINOSITES MIDDENDORFENSIS sp. nov.

Plate VIII, figure 13.

Description.—Leaves or leaflets ovate-lanceolate in outline, with a pointed apex and rounded base, 3 centimeters in length by 1.4 centimeters in greatest width, which is in the middle part of the leaf. Midrib thin. Secondaries thin, open, five or six pairs, slightly curved, ascending at angles of 45 to 50°.

This species is of rare occurrence and vague relationship, although it seems to be most closely related to the leguminous leaves usually referred to the form-genus Leguminosites.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

LEGUMINOSITES ROBINIIFOLIA Berry.

Plate IX, figure 11.

Leguminosites robiniifolia Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 196.

Description.—Leaflets sessile, ovate to ovate-elliptical in outline. Length about 2.5 centimeters. Greatest width, 1.3 to 1.5 centimeters, at a point slightly nearer the base than the apex. Both the apex and the base are obtusely rounded, the base broadly and the apex more narrowly. Midrib fairly stout. Secondaries consist of about five alternate to opposite pairs, slender, regularly curved, and approximately parallel, branching from the midrib at angles of about 45° or slightly more, camptodrome.

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[1] Die Flora der böhmischen Kreideformation, pt. 2, 1883, p. 3, Pl. I, figs. 6–10.

[2] Newberry, J. S., The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 94, Pl. XLII, figs. 49, 50.

This well-marked species is entirely distinct from previously described forms and is remarkably close to the leaves of the existing *Robinia pseudacacia* Linné of the eastern United States, which fact has led to the specific name chosen for it. It was described recently by the writer from material collected from the Black Creek formation at Court House Bluff on Cape Fear River in North Carolina.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley, Aiken County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Order GERANIALES.

Family RUTACEÆ.

Genus CITROPHYLLUM Berry.

CITROPHYLLUM ALIGERUM (Lesquereux) Berry.

Ficus aligera Lesquereux, Mon. U. S. Geol. Survey, vol. 17, 1892, p. 84, Pl. X, figs. 3–6.
Ficus aligera Berry, Ann. Rept. State Geologist, New Jersey, for 1905, 1906, p. 139.
Ficus aligera Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 172.
Citrophyllum aligerum Berry, idem, vol. 36, 1909, p. 258, Pl. XVIIIa, figs. 1–8.

Description.—The following description is given in the reference last cited:

> Leaves small, elliptical to ovate or ovate-lanceolate, coriaceous, varying from 2.5 to 6 centimeters in length by 1.8 to 3.2 centimeters in breadth. Margin entire, occasionally slightly undulate. Apex rounded or obtusely acuminate. Base rounded, subtruncate, or cuneate. Petiole stout, 0.7 to 2 centimeters in length, conspicuously alate. The petiolar wings may be oblong-lanceolate or obovate; together they are from 2.5 to 5 millimeters in width, averaging about 3.5 millimeters. Midrib stout. Secondaries fine, more or less obscured by the coriaceous leaf substance, about nine alternate pairs, branching from the midrib at angles of from 45 to 50°, parallel, camptodrome.

These curious leaves (morphologically leaflets) were described by Lesquereux in 1892 from the Dakota sandstone as a species of Ficus and compared with *Ficus bumelioides* Ettingshausen and *Ficus mudgei* Lesquereux, neither which has alate petioles and the first has an emarginate apex. Subsequently the same leaves were found in the Magothy formation of New Jersey, and only recently a single small leaf was found in the upper part of the Raritan formation of South Amboy, N. J. They exhibit considerable variety in outline, but all have exactly the same aspect and conspicuous, more or less alate petioles. They appear to be closely related to the leaves of the modern genus Citrus. The latter have exactly the same texture and venation, the same variability in outline and marginal undulations, the same stout midrib, and conspicuously alate petioles. In examining a suite of specimens of the latter and comparing them with the fossils the conclusion seems to be irresistible that they are related, and the writer consequently referred the fossils to a new genus with a name that emphasized this relationship to the modern genus. All the more complete leaves of this species were figured by the writer in 1909, as well as some recent Citrus leaves for comparison with them. Possible arguments against the present view may be based on the theory that the modern alate petioles are derived from ancestors with compound leaves; in fact, some modern species still have trifoliate leaves, and if this were true of the fossils as well it would require considerable rapidity of evolution in the genus previous to the middle part of the Cretaceous. The modern leaves abscise from the top of the petiole and would be unlikely to occur as fossils with the petiole attached; neither can any indication of such an abscission line be made out in the fossils. This is the most difficult argument to combat. However, modern leaves are sometimes shed in their entirety, and we are justified in assuming the occasional fall of leaves before maturity when the abscission layer of cells had not yet become weakened. The cause might be violent winds, the passage of large animals like some of the Cretaceous dinosaurs, or weakened conditions resulting from attacks of insects, or of fungous diseases. The species is also found in the Magothy, Tuscaloosa, and Dakota formations.

The South Carolina occurrence of this species is based upon the incomplete but characteristic leaves and tends to confirm the doubtful identification of this form in the Black Creek formation of North Carolina.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; Miles Mill, Aiken County. (Collected by E. W. Berry and Earle Sloan.)

Collections.—U. S. National Museum.

Order **EUPHORBIALES.**

Family **EUPHORBIACEÆ.**

Genus **CROTONOPHYLLUM** Velenovsky.

CROTONOPHYLLUM PANDURÆFORMIS sp. nov.

Plate VII, figures 5–10.

Description.—Leaves of variable size, entire and ovate-lanceolate or irregular panduriform in outline, about 8 to 10 centimeters in length by 3 to 4 centimeters in greatest width, which is in the basal half of the leaf. General outline ovate, separated by a sharp lateral sinus on each side into a broad basal portion with full rounded margins and an upper narrower portion which is more or less rounded or elongated. In some specimens the sinus is wanting on one side; it may be wanting on both sides and the leaf be ovate-lanceolate in outline, as it often is in the only other known species of the genus. This is the habit of a number of specimens from the Miles Mill locality. Apex bluntly pointed. Base slightly recurrent to the stout petiole, which is of considerable length. Texture coriaceous. Midrib stout. Secondaries numerous, rather stout, branching from the midrib at angles of about 45°, parallel, camptodrome below and in some specimens also in the apical portion of the leaf, in which case they pursue an upwardly curved course. In other specimens they are straight in the apical half of the leaf, and their ends are connected by a nearly straight marginal vein, which is the continuation of some lower secondary; in fact, the regularly camptodrome lower secondaries are parallel with the margin before they finally inosculate.

These curious leaves are not uncommon in the South Carolina Cretaceous, though they are generally incomplete. They are wholly unlike any known American Cretaceous leaves, although they suggest the leaf described from the Upper Cretaceous of Vancouver Island by Dawson as *Liriodendron succedens.*[1] In the writer's opinion Dawson's leaf is not a Liriodendron, but as Dawson's figures are inaccurate, and as the writer has not seen the original material, his opinion is not conclusive. The genus Crotonophyllum was proposed by Velenovsky for leaves from the Cenomanian of Vyserovic, Bohemia, which are very similar to the present species. A single species, *Crotonophyllum cretaceum,*[2] was described and compared with the existing species of Croton, but as the discussion is in Bohemian the description is not readily accessible to English readers. The illustrations, however, are ample and depict a leaf which is surely congeneric with the South Carolina fossils.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; near Langley and Miles Mill, Aiken County; Rocky Point, Sumter County. (Collected by L. W. Stephenson, E. W. Berry, and Earle Sloan.)

Collections.—U. S. National Museum.

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[1] Trans. Roy. Soc. Canada, vol. 11, sec. 4, 1894, p. 62, Pl. VIII, fig. 26.

[2] Velenovsky, J., Květena českého cenomanu, 1889, p. 20, Pl. V, figs. 4–11.

Order SAPINDALES.

Family SAPINDACEÆ.

Genus SAPINDUS Linné.

SAPINDUS MORRISONI Heer.

Plate IX, figure 6.

Sapindus morrisoni Heer (Lesquereux MS.), Flora fossilis arctica, 1882, vol. 6, Abth. 2, p. 96, Pls. XL, fig. 1; XLI, fig. 3; XLIII, figs. 1a, 1b; and XLIV, figs. 7 and 8.

Sapindus morrisoni Heer, idem, vol. 7, 1883, p. 39, Pl. LXV, fig. 5.

Sapindus morrisoni Lesquereux, The Cretaceous and Tertiary floras, 1883, p. 83, Pl. XVI, figs. 1 and 2.

Sapindus morrisoni Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 158, Pl. XXXV, figs. 1 and 2.

Sapindus morrisoni Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 422, Pl. XXXVI, fig. 4.

Sapindus morrisoni Knowlton, Twenty-first Ann. Rept. U. S. Geol. Survey, 1901, p. 317, pt. 7.

Sapindus morrisoni Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 83, Pl. XLVII, figs. 2 and 3.

Sapindus morrisoni Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 78.

Sapindus morrisoni Berry, Ann. Rept. State Geologist New Jersey for 1905, 1906, pp. 138 and 139.

Sapindus morrisoni Hollick, Mon. U. S. Geol. Survey, vol. 50, 1907, p. 90, Pl. XXXIII, figs. 16–20.

Description.—Leaves pinnately compound. Leaflets large, subcoriaceous, entire, lanceolate in outline, about 10 to 15 centimeters in length or in a few specimens larger, by 2 to 3 centimeters in greatest width. Base cuneate or rounded, generally inequilateral. Midrib stout. Secondaries stout, bowed, rather open, approximately parallel, camptodrome.

These leaflets are usually found detached, as in the few specimens found near Langley, S. C., although some of the material from the west shows the habit. This species was described by Lesquereux and named in allusion to the type locality. As Lesquereux's report on Cretaceous and Tertiary floras was not published promptly, it happened that Heer had meanwhile published this species, based on Greenland material and identified by means of some of the plates of Lesquereux's work which the latter had sent to him, so that the species must be credited to Heer. It occurs at both the Atane and Patoot horizons in Greenland and is a common form in the Woodbine sand of Texas, which is regarded as the southern equivalent of the Dakota sandstone. In the east it is probably confined to post-Raritan deposits, although there is some doubt regarding the age of the morainic material on Staten Island from which it has been recorded by Hollick. It is common in the Magothy formation of New Jersey, but has not heretofore been recorded from the southern Coastal Plain, although it will probably be found to be a member of the Tuscaloosa flora when the Alabama collections are thoroughly studied.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley, Aiken County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Family CELASTRACEÆ.

Genus PACHYSTIMA Rafinesque.

PACHYSTIMA? CRETACEA sp. nov.

Plate X, figure 6.

Description.—Leaves of small size, oblong or obovate in outline, with a rounded apex and a narrowed descending base, about 2 centimeters in length by 3 millimeters in greatest width. Texture coriaceous. Petiole short and stout. Midrib stout. Secondaries numerous, fine, immersed, ascending.

This species is totally unlike any described fossil forms and closely resembles the leaves of the existing species of Pachystima, of which only two are known, one from the East and one from the Rocky Mountain area. They are shrubs of dry situations with evergreen, more or less revolute leaves. The writer feels much doubt about this identification, and it is possible that this species represents the excessively narrowed leaves of *Acaciaphyllites grevilleoides* Berry collected from the same locality. Pachystima is unknown in the fossil state elsewhere except for a recently described species from the Miocene of Florissant, Colo.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Genus **CELASTROPHYLLUM** Goeppert.

CELASTROPHYLLUM ELEGANS Berry.

Plate XIV, figure 11.

Celastrophyllum elegans Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 84, Pl. XLIII, fig. 6.
Celastrophyllum elegans Berry, Bull. Torrey Bot. Club, vol. 32, 1905, p. 46, Pl. II, fig. 1.

Description.—Leaves obovate in outline with a broadly rounded apex and cuneate pointed base, 6 to 8 centimeters in length by 2 centimeters or slightly more in greatest width, which is in the middle part of the leaf. Margin entire below with undulate shallow teeth above. Secondaries numerous, branching at angles of more than 45°, rather straight, parallel, camptodrome.

This species is quite distinct from any other species of Celastrophyllum, although it shows some points of similarity with the abundant Raritan and Dakota species. It was described from the Magothy formation of New Jersey, the occurrence in South Carolina being the first recorded outside of the type area. It is rare in South Carolina and not especially well preserved, the material differing from the type in the somewhat more numerous secondaries.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

CELASTROPHYLLUM CRENATUM Heer.

Celastrophyllum crenatum Heer, Flora fossilis arctica, vol. 7, 1883, p. 41, Pl. LXII, fig. 21.
Celastrophyllum crenatum Smith, On the geology of the Coastal Plain of Alabama, 1894, p. 348.
Celastrophyllum crenatum Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 99, Pl. XLVIII, figs. 1–19.
Celastrophyllum crenatum Berry, Bull. Torrey Bot. Club, vol. 34, 1907, p. 197, Pl. XIII, fig. 5.

Description.—Leaves very variable in size, 2 to 8 centimeters in length by 1 to 5 centimeters in width, ovate or eliptical in outline, broadly rounded above, narrowed and generally inequilateral below. Margins entire below, coarsely toothed above, with somewhat variable, rounded, crenate, or crenato-dentate teeth. A few specimens are entire throughout and some have a markedly inequilateral base. Midrib fairly stout. Secondaries numerous, nine or ten pairs, subopposite, branching from the midrib at angles somewhat in excess of 45°, slightly curved upward and parallel, branching near the margin to form festoons from which branches enter the marginal teeth.

This species was described by Heer from the Patoot beds of Greenland and unfortunately only a single small leaf was figured. The Raritan leaves, which are abundant, grade into much larger forms that are also present in the Black Creek formation of North Carolina and the Tuscaloosa formation of Alabama.

The species is rare in South Carolina, fragmentary specimens being sparsely represented in the Middendorf collections. The genus is characteristic of the late Lower Cretaceous and early Upper Cretaceous of eastern North America and is not known anywhere from beds of Montana or Senonian age.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

CELASTROPHYLLUM CAROLINENSIS sp. nov.

Plate XIII, figures 1–5.

Description.—Leaves lanceolate in outline, with a pointed apex and a cuneate base, about 14 centimeters in length by 2.9 centimeters in greatest width, which is about midway between the apex and the base, tapering equally in both directions. Midrib stout, rather flexuous. Secondaries numerous, thin, branching from the midrib at acute angles of 45° or less, curving upward, usually camptodrome, a few craspedodrome in the upper part of the leaf, sending tertiary branches into the marginal teeth. Margin entire for a short distance at the base, above which it is crenate or biconvex, the teeth large and interspersed with smaller subordinate teeth of the same character. Leaf substance thin.

This striking form is rather common at the locality near Langley, but all the leaves are much broken, though fragments of all parts of the leaf are present, and fully warrant the restoration shown in figure 5 of the plate.

This species has been compared with a very large amount of existing material in the herbaria of the New York Botanical Garden and the United States National Museum. It shows analogies with a variety of existing genera, as for example, Cunonia, Clerodendron, Symplocos, Ternstromia, Callicarpa, Panax, and other forms, but is believed to find its nearest relatives among the Celastraceæ. It is not close to any described fossil species, although there is a general resemblance to a number of the American Cretaceous species of Celastrophyllum. There is also a general resemblance to *Grevilleophyllum constans*[1] and *Aralia coriacea*,[2] both Cenomanian species described by Velenovsky from Bohemia. Leaves of this sort have also been referred to Dryandroides (cf. *quercinea* Velenovsky), Myrica (cf. *serrata* Velenovsky), Quercus, and Fraxinus.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley, Aiken County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Family ANACARDIACEÆ.

Genus RHUS Linné.

RHUS DARLINGTONENSIS sp. nov.

Plate IX, figures 7 and 8.

Description.—Leaflets large, broadly ovate in outline, with an obtusely pointed apex and a rounded base, about 9 or 10 centimeters in length by 4.5 centimeters in greatest width, which is the middle or lower half of the leaf. Texture subcoriaceous. Margin dentate, crenate, or scalloped, with subordinate crenulations. Midrib straight, fairly stout. Secondaries consisting of about nine subopposite or alternate pairs, branching from the midrib at obtuse angles of about 60°, approximately parallel, slightly curved, craspedodrome, terminating in the main marginal teeth and sending short outwardly and downwardly directed branches to the subordinate teeth. Bulk of tertiaries transverse.

This large and evidently handsome species is based upon abundant, but very poorly preserved material, the two best specimens being those figured. In general appearance it suggests the less elongate and broader leaves of *Myrica elegans* Berry, but it is a much larger and broader leaf with more open secondaries.

Five Cretaceous species of Rhus have been described, three from the Dakota sandstone and two from Europe, one of the latter being also recorded from Glen Cove, Long Island, by Hollick. The South Carolina species is very different from all these and is much more modern in appearance, suggesting a number of Tertiary species of Rhus and closely resembling the larger, less elongate leaves of the existing *Rhus glabra* Linné; in fact, leaves of the latter can be selected which, except for the more acute teeth, are exactly like this Cretaceous form.

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[1] Velenovsky, J., Die Flora der böhmischen Kreideformation, pt. 2, 1883, p. 3, Pl. I, figs. 6–10.

[2] Idem, pt. 3, 1884, p. 11, Pls. I, figs. 1–9; II, fig. 2.

Occurrence.—Black Creek formation, near Darlington, Darlington County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Order **THYMELEALES.**

Family **LAURACEÆ.**

Genus **LAURUS** Linné.

LAURUS PLUTONIA Heer.

Plates XI, figure 2, and XIII, figure 6.

Laurus plutonia Heer, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 75, Pls. XIX, figs. 1d, 2-4; XX, figs. 3a, 4-5; XXIV, fig. 6b; XXVIII, figs. 10 and 11; and XLII, fig. 4b.

Laurus plutonia Heer, idem, vol. 7, 1883, p. 30, Pls. LVIII, fig. 2, and LXII, fig. 1a.

Laurus plutonia Velenovsky, Die Flora der böhmischen Kreideformation, pt. 3, 1884, p. 1, Pl. IV, figs. 2-4.

Laurus plutonia Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 91, Pls. XIII, figs. 5 and 6, and XXII, fig. 5.

Laurus plutonia Lesquereux, Geol. and Nat. Hist. Survey Minnesota, vol. 3, pt. 1, 1895, p. 14, Pls. A, fig. 6, and B, fig. 5.

Laurus plutonia Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 85, Pl. XVI, figs. 10 and 11.

Laurus plutonia Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 60, Pl. IV, figs. 6 and 7

Laurus plutonia ? Gould, Am. Jour. Sci., 4th ser., vol. 5, 1898, p. 175.

Laurus plutonia Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 79, Pl. L, figs. 9-11

Laurus plutonia Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 77, Pl. III, fig. 1.

Laurus plutonia Berry, idem, vol. 33, 1906, p. 178.

Laurus plutonia Berry, Ann. Rept. State Geologist New Jersey for 1905, 1906, pp. 138 and 139.

Laurus plutonia Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 80, Pls. XXVII, figs. 9 and 11, and XXVIII, figs. 1 and 2.

Description.—Leaves lanceolate in outline, usually tapering almost equally in both directions but some specimens less acute at the base. Length, 7 to 11 centimeters; greatest width, 1.5 to 2.5 centimeters. Midrib fairly stout. Petiole short and stout, 6 to 15 millimeters in length. Secondaries slender, eight or more alternate pairs, camptodrome.

This species was described by Heer from the Atane beds of Greenland and a large number of somewhat variable and fragmentary specimens were figured. Prof. Newberry subsequently recorded specimens from the Raritan formation of New Jersey without giving any specific localities. Those figured show leaves which are relatively wider than is usual with leaves of this species, but these are comparable with some of Heer's Greenland specimens.[1] Entirely typical leaves occur in the top layer of the Raritan at the Hylton pits in southwestern New Jersey.

Subsequent to its description by Heer this species was recorded from a very large number of Cretaceous plant beds, so that its present range, both geographic and geologic, is rather wide. Some of these records the writer believes to be not altogether above question, however, among those of which doubt is felt being the identifications of the forms from the Cenomanian of Bohemia by Velenovsky.

It is evidently a rare plant in the Raritan but becomes abundant in immediately succeeding floras, being common in that of the Dakota sandstone and in the Magothy formation at a number of localities in New Jersey and Maryland. It is a common form in the insular Cretaceous floras and also occurs in the South Atlantic Coastal Plain. Supposed fruits are figured by Heer.[2] In South Carolina this species is represented by typical leaves that are not at all uncommon. It has not been detected in the North Carolina Cretaceous, although it ranges from the base to the top of the Tuscaloosa formation in Alabama.

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[1] Op. cit., vol. 6, Abth. 2, 1882, Pls. XX, figs. 5 and 11.

[2] Op. cit., Pl. XLII, fig. 4b.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf. Chesterfield County; near Langley, Aiken County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

LAURUS ATANENSIS nom. nov.

Plate XIII, figure 7.

Laurus angusta Heer, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 76, Pls. XX, figs. 1b and 7, and XLIII fig. 1c (non Rafinesque).

Laurus angusta Heer, idem, vol. 7, 1883, p. 30, Pl. LVII, fig. 1b.

Laurus angusta Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 93, Pl. XVI, fig. 7.

Laurus angusta Hollick, Bull. New York Bot. Garden, vol. 3, 1904, p. 408, Pl. LXX, figs. 10 and 11.

Laurus angusta Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 81, Pl. XXVII, figs. 11 and 12.

Description.—Leaves entire, linear-lanceolate, tapering about equally to the acuminate apex and base. Length, 12 centimeters or less; some of Heer's Greenland material ranging considerably under this dimension. Width, about 1.5 centimeters. Midrib relatively thin. Secondaries thin, somewhat widely separated, branching from the midrib at acute angles, 45° or less, nine to twelve alternate pairs, finally ascending along the margin, camptodrome. Tertiaries forming the characteristic areolation of the genus.

Heer originally compared this species with *Laurus plutonia*, pointing out that it was more linear and acuminate. He also remarks that it is somewhat smaller, but this generalization has been found not to hold good, even for the Greenland material. The primaries are sparser and more ascending than in *Laurus plutonia* and the more linear form gives the leaf a decidedly different aspect. There can be no doubt that the two are perfectly distinct species, naturally possessing certain lauraceous characters in common.

Heer's name for this species is preoccupied by that given by Rafinesque to an existing species, so that a new name is necessary, the one proposed being given in allusion to the type locality.

Laurus atanensis was described from the Atane beds of Greenland and was subsequently recorded from the Patoot beds. Lesquereux identified it from the Dakota sandstone of Kansas and Hollick has recorded it from the clays of Northport, Long Island, which are probably of Magothy age. It has not been detected from the southern Atlantic Coastal Plain, although it may well be present in the unstudied collections from the Magothy formation of Maryland and from the Tuscaloosa formation of Alabama.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Genus **LAUROPHYLLUM** Goeppert.

LAUROPHYLLUM ELEGANS Hollick.

Plate XII, figure 6.

Laurus plutonia Hollick, Trans. New York Acad. Sci., vol. 11, 1892, p. 99, Pl. III, figs. 3 and 4.

Laurus plutonia Hollick, idem, vol. 12, 1893, p. 236, Pl. VI, fig. 1 (non Heer).

Proteoides daphnogenoides Hollick, Annals New York Acad. Sci., vol. 2, 1898, p. 420, Pl. XXXVI, fig. 2 (non Heer).

Laurophyllum elegans Hollick, The Cretaceous flora of New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 81, Pl. XXVII, figs. 1–5.

Laurophyllum elegans Berry, Bull. Torrey Bot. Club, vol. 37, 1910, pp. 26, 198.

Description.—Leaves elongate-lanceolate, somewhat flexuous, about 12 or 13 centimeters in length by about 2 centimeters in greatest width, which is about midway between the apex and the base; from this point they narrow gradually apically into an attenuated acuminate, usually curved tip, and basally into a long, narrowly cuneate base. Midrib and petiole stout. Secondaries numerous, usually less close and somewhat coarser than in *Laurophyllum nervil-*

losum, branching from the midrib at an acute angle below, which becomes more open above the base of the leaf; they are usually more curved than in *Laurophyllum nervillosum* and more distinctly camptodrome. Tertiaries transverse throughout.

These leaves were recorded originally by Hollick as *Laurus plutonia* Heer and were later compared with *Laurus angusta* Heer, which latter species they resemble more than they do the former. In outline they are not unlike *Laurophyllum angustifolium* Newberry, from the Raritan formation of Woodbridge, N. J., but differ decidedly in venation. They are also similar but quite distinct from *Laurophyllum nervillosum* Hollick, of the East, and *Laurophyllum reticulatum* Lesquereux, of the Dakota sandstone.

The type was obtained from transported materials associated with the terminal moraine, from which numerous specimens have been collected. Those from Tottenville, Staten Island, are undoubtedly of Raritan age, but those from Glen Cove may have come originally from the Magothy formation, although they are probably Raritan. The species is certainly known from the upper part of the Raritan at South Amboy, N. J., and is common in the Magothy formation of Maryland. It is sparsely represented in the Black Creek formation of North Carolina and is not uncommon near Middendorf, the latter specimens being slightly broader and consequently having fewer secondaries ascending than the type specimens.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

LAUROPHYLLUM NERVILLOSUM Hollick.

Plate XII, figure 7.

Proteoides daphnogenoides Hollick, Annals New York Acad. Sci., vol. 2, 1898, p. 420, Pl. XXXVI, figs. 1 and 3 (non Heer).

Laurophyllum nervillosum Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 82, Pl. XXVII, figs. 6, 7.

Laurophyllum nervillosum Berry, Bull. Torrey Bot. Club, vol. 36, 1909, p. 255.

Description.—Leaves of comparatively large size, oblong-lanceolate in outline, about 15 centimeters in length by about 2.5 centimeters in greatest width, which is about midway between the apex and the base. Apex acuminate. Base pointed, narrowly cuneate. Midrib stout. Secondaries thin, close, parallel, branching from the midrib at angles not exceeding and usually somewhat less than 45°, ascending, nearly straight or somewhat flexuous, connected by transverse nervilles, branching and inosculating near the margin, where they merge in the tertiary venation.

This species was described originally from the terminal moraine at Tottenville, Staten Island, and undoubtedly represents transported Raritan materials. It is also present in the lower part of the Raritan formation at Milltown, N. J., and is not uncommon in the South Carolina Cretaceous. It is somewhat like *Laurophyllum lanceolatum* Newberry, but has a markedly different venation and a less lanceolate outline. It is also quite close to *Laurophyllum elegans* Hollick, which is, however, a more slender lanceolate leaf, having narrowly produced apex and base and a somewhat coarser venation, with camptodrome secondaries, less close and more curved.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. Black Creek formation, near Darlington, Darlington County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Genus **CINNAMOMUM** Blume.

CINNAMOMUM NEWBERRYI nom. nov.

Plate IX, figures 12 and 13.

This species is described in the section of this report dealing with the Upper Cretaceous flora of Georgia (pp. 117–118). The South Carolina remains referred to it are few and poor, and include fragments of rather large leaves from Rocky Point and doubtfully determined fragments from the banks of Congaree River.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County; right bank of Congaree River, about 25 miles below Columbia, Lexington County. (Collected by E. W. Berry, B. L. Miller, and M. W. Twitchell.)

Collections.—U. S. National Museum.

CINNAMOMUM MIDDENDORFENSIS sp. nov.

Plates VIII, figure 14, and IX, figure 1.

Description.—Leaves lanceolate in outline, somewhat widened toward the acute base. Length 8 to 10 centimeters; greatest width, 1.7 to 2.4 centimeters in the basal half of the leaf, the margins narrowing gradually upward to produce the very much extended, acutely pointed apex. Primaries three, from the top of the petiole, the midrib being slightly the more prominent. Angles of divergence acute, 20° to 25°. The lateral primaries assume a course approximately parallel to the midrib about half way between the latter and the margins and extend well into the tip of the leaf, finally joining a short, upwardly curving secondary from the midrib. Tertiaries numerous, transverse, nearly straight, and parallel. From the extreme base on either side a marginal vein extends upward from one-third to one-half the distance to the apex, joining the ends of the transverse tertiaries which extend outward from the lateral primaries, above which upwardly curved camptodrome secondaries are given off. Texture coriaceous.

This is an exceedingly well-marked and handsome species, entirely distinct from any Cretaceous forms hitherto described. It is a typical Cinnamomum in all its characteristics, although it may be compared with a variety of tropical genera such as Leucosyke and Zizyphus. It bears some resemblance to the Bohemian Cenomamian forms described by Velenovsky[1] as *Cocculus cinnamomeus* and is strikingly like certain existing Oriental species of Cinnamomum, as, for example, *Cinnamomum chinense* Blume or *Cinnamomum albiflorum* Rees. It is also close to various Tertiary species referred to this genus.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Order **MYRTALES.**

Family **MYRTACEÆ.**

Genus **EUCALYPTUS** L'Héritier.

EUCALYPTUS ANGUSTA Velenovsky.

Plate XIV, figure 2.

Eucalyptus angusta Velenovsky, Die Flora der böhmischen Kreideformation, pt. 4, 1885, p. 3, Pl. III, figs. 2–12.
Eucalyptus angusta Velenovsky, Květena českého cenomanu, 1889, p. 21, Pl. VI, fig. 1.
? *Eucalyptus angusta* Saporta, Flore fossile du Portugal, 1894, p. 207, Pl. XXXVI, fig. 12.
Eucalyptus angusta Berry, Bull. Torrey Bot. Club, vol. 36, 1909, p. 260, Pl. XVIII, fig. 5.

Description.—The following is Velenovsky's description of this interesting species:

> Blätter lineal, schmal lineallanzettlich, in der Mitte oder in der unteren Hälfte am breitesten, ganzandig, vorne in eine sehr lange Spitze vorgezogen und mit einem harten Dorn beendet. Der Primärnerv gerade, ziemlich stark, zur Spitze hin verdünnt. Die Secundärnervenahlrich, unter spitzen Winkeln entspringend, am Rande durch einen Saumnerv untereinander verbunden. Der Blattsteil gerade, etwa 1 cm. lang, stark.

This species is exceedingly common at a number of localities in the Perucer-schichten of Bohemia (Cenomanian), where Velenovsky subsequently found fruit-bearing twigs which he described and figured in 1889 and which, it would seem, conclusively establish the botanic relations of these leaves.

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[1] Velenovsky, J., Die Flora der böhmischen Kreideformation, pt. 4, 1885, p. 4 (65), Pl. VIII (31), figs. 16–21.

Subsequently Saporta recorded this species from the Albian beds of Portugal; the latter material is, however, rather incomplete and open to question. Recent collections in our Atlantic Coastal Plain show that this species was present in considerable abundance on this side of the Atlantic at the same time that it flourished in Europe. It has been collected from the upper part of the Raritan formation at South Amboy, N. J., where it is common, and from the Black Creek formation of South Carolina, where it is associated with *Araucaria bladenensis* Berry just as it is in Georgia. It may be somewhat more fully characterized as follows: Leaves alternate or scattered, mostly elongated, linear-lanceolate, many falcate, 4.5 to 15 centimeters in length by 5 to 13.5 millimeters in width, with an attenuated acute tip and a narrowly cuneate base declining to the short and stout petiole. Midrib moderately stout below, becoming attenuated above. Secondaries very numerous, fine, and close, about 1 millimeter apart, parallel, rather straight; they branch from the midrib at acute angles of about 30° or slightly less and run with slight curvature to join the well-marked but fine marginal hem, which shows in all the American material and in most of the illustrations of the foreign material.

In all respects this is one of the most characteristically Eucalyptus-like species of the many which have been identified as such; and its totality of characters, combined with the presence of attached fruits in the Bohemian material, which are not unlike some of those of modern forms, renders the identification very satisfactory.

Occurrence.—Black Creek formation, right bank of Black Creek, below Williamson's bridge, Florence County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

EUCALYPTUS GEINITZI (Heer) Heer.

Plates XIII, figures 8–12, and XIV, figure 1.

Myrtophyllum geinitzi Heer, Flora von Moletein, 1872, p. 22, Pl. XI, fig. 3, 4.
Myrtophyllum geinitzi Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 116, Pl. XXXII, figs. 14–17.
Eucalyptus geinitzi Heer, idem, vol. 6, Abth. 2, 1882, p. 93, Pls. XIX, fig. ic, and IV, fig. 1, 13.
Eucalyptus geinitzi Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 138, Pl. XXXVII, fig. 20.
Myrtophyllum warderi Lesquereux, idem, 1892, p. 136, Pl. LIII, p. 53, fig. 10.
Eucalyptus? *angustifolia* Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 111, Pl. XXXII, figs. 1, 6, and 7 (non Desvaux 1822).
Eucalyptus geinitzi Newberry, idem, 1896, p. 110, Pl. XXXII, figs. 2 and 12 (non figs. 15, 16).
Eucalyptus geinitzi Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 60, Pl. IV, figs. 1–3.
Eucalyptus geinitzi Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 87, Pl. LIII, fig. 3.
Eucalyptus? *angustifolia* Hollick, idem, vol. 3, 1904, p. 408, Pl. LXX, figs. 8 and 9.
Eucalyptus geinitzi Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 78, pl. IV, fig. 5.
Eucalyptus geinitzi Berry, idem, vol. 33, 1906, p. 180.
Eucalyptus geinitzi Berry, idem, vol. 34, 1907, p. 201, Pl. XV, fig. 4.
Eucalyptus geinitzi Berry, Johns Hopkins Univ. Circ., new ser., No. 7, 1907, p. 81.
Eucalyptus geinitzi Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 96, Pl. XXXV, figs. 1–8, 10–12.
Myrtophyllum warderi Hollick, idem, p. 97, Pl. XXXV, fig. 13.
Eucalyptus angustifolia Hollick, idem, 1907, p. 95, Pl. XXXV, figs. 9, 14, and 15.

Description.—Leaves lanceolate in outline, broadest near the middle and almost equally tapering in both directions to the acute apex and base. There is considerable variation in size, the South Carolina leaves averaging about 15 centimeters in length by 2.2 centimeters in greatest width. The petiole is very stout, as is the prominent midrib, which leaves a sharp groove in impressions of the lower surface of the leaf. Secondaries numerous, thin, branching from the midrib at acute angles, about 45°, and running with only a slight curvature to the marginal vein, which is either almost straight when the secondaries are close set, or more or less bowed when the secondaries are some little distance apart, as they are in many specimens.

This species has an especially wide range. It was described originally from the Cenomanian of Moravia, and has since been recorded from a number of other European localities, from the Atane beds of Greenland and the Dakota sandstone of the West, and from Marthas Vineyard to Alabama along the Atlantic Coast. The South Carolina material is abundant and characteristic, and is certainly identical with the type, whatever may be thought of some of the leaves which have been identified with this species.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; near Langley, Aiken County; Rocky Point, Sumter County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

EUCALYPTUS WARDIANA Berry (?).

Plate XIV, figures 3 and 4.

Eucalyptus ? dubia Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 87, Pl. LII, fig. 1 (non Ettingshausen).
Eucalyptus wardiana Berry, Bull. Torrey Bot. Club, vol. 32, 1905, p. 47.
Eucalyptus wardiana Berry, idem, vol. 33, 1906, p. 180.
Eucalyptus wardiana Berry, Ann. Rept. State Geologist New Jersey for 1905, 1906, pp. 138, 139, and 141.

Description.—Leaves entire, linear-lanceolate in outline, with an acute apex and cuneate base, about 10 or 12 centimeters in length by 1 to 1.6 centimeters in greatest width. Petiole stout, of considerable length. Midrib stout. Secondaries numerous, approximately straight and parallel, branching from the midrib at angles of 45° to 50°, their ends connected by a marginal vein, which is straight and close to the margin, with which it is parallel. This species was originally described by the writer from New Jersey, and is found to a characteristic species of the Magothy formation in that State as well as in Delaware and Maryland. It is very similar to the upper Raritan species, *Eucalyptus linearifolia* Berry (*Eucalyptus nervosa* Newberry), and probably the forms from the Tuscaloosa formation of Alabama correlated by Ward with the latter species are referable to this species. The South Carolina remains agree with the type material from New Jersey better than is indicated by the figures, for the type figures are not accurate.

This species may also be compared with the contemporaneous *Eucalyptus angusta* Velenovsky, which is, however, a smaller, falcate, less linear leaf with still more numerous and more ascending secondaries.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Order **UMBELLALES.**

Family **ARALIACEÆ.**

Genus **HEDERA** Linné.

HEDERA PRIMORDIALIS Saporta.

Hedera primordialis Saporta, Le monde des plantes, 1879, p. 200, figs. 29, 1 and 2.
Hedera primordialis Velenovsky, Die Flora der böhmischen Kreideformation, pt. 1, 1882, p. 19, Pls. VIII, fig. 7; IX, figs. 4 and 5; and X, figs. 3 and 4.
Hedera primordialis Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 113, Pls. XIX, figs. 1 and 9 and XXXVII, figs. 1–7.
Hedera primordialis Berry, Bull. Torrey Bot. Club, 1907, vol. 34, p. 201, Pl. XVI.

Description.—Leaves elliptical, reniform or cordate in outline, very variable in size and shape. Length 3 to 12 centimeters, width 3.2 to 12 centimeters, generally broader than long. Apex rounded or obtusely pointed, in some specimens slightly emarginate. Margin somewhat irregular but entire. Base varies from truncate to deeply cordate. Petiole long and stout, generally not preserved. Venation palmate from the top of the petiole. Primaries range in number from three to seven, usually five or seven, of which the midrib is the stoutest, especially in the smaller leaves. The lowest pair of primaries, which are approximately parallel with the basal margins of the leaf, are smaller in size than the others and should be regarded as secondaries. The primaries are then normally five in number, curved and camptodrome.

This species was figured by Saporta in 1879 from the Cenomanian of Bohemia and described three years later by Velenovsky from the same horizon. Heer identified rather fragmentary remains from the Atane beds of Greenland with this species, which is also abundant in the Raritan formation of Woodbridge, N. J., and in the Black Creek formation of North Carolina. It varies greatly in size and appearance, some of the smaller specimens from abroad suggesting the genus Cercis, whereas the smaller Raritan leaves suggest somewhat the genus Ficus. Of these variable specimens the writer is disposed to consider as typical those shown in Velenovsky's Plate X, figure 4, and Saporta's figure 2, as well as various Woodbridge specimens, which are, however, mostly incomplete.

This is a remarkably widespread species, and is better characterized where it does occur than is usual in cosmopolitan types. Although the modern representation of this genus is reduced to two species in Europe and northern Africa and a third in Japan, it seems to have been a more or less prominent type in the Cretaceous and Tertiary floras of the globe. In addition to the present species, which has the wide range previously mentioned, 8 or 10 additional Cretaceous species, mostly American, are known. The Eocene, both of America and Europe, furnishes six or eight species, the Oligocene of Europe and the Arctic regions one or two species, and the Miocene and Pliocene two or three additional. The modern Old World *Hedera helix* Linné is recorded from the Pleistocene (Interglacial) of England, Italy, and the Paris basin, and one of the upper Miocene species appears also to have survived into the Italian Pleistocene. Although so abundant in our Cretaceous floras, it is not a native plant in the existing flora of North America.

Occurrence.—Black Creek formation, Peedee River, about 6 miles below Cheraw, Chesterfield County; near Darlington, Darlington County. (Collected by E. W. Berry and L. W. Stephenson.)

Collections.—U. S. National Museum.

Order **ERICALES.**

Family **ERICACEÆ.**

Genus **ANDROMEDA** Linné.

ANDROMEDA NOVÆCÆSAREÆ Hollick.

Plate XIV, figures 5 and 6.

Andromeda novæcalcareæ Smith, On the geology of the Coastal Plain of Alabama, 1894, p. 348.
Andromeda novæcæsareæ Hollick, in Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 121, Pl. XLII, figs. 9–12, 28–31.
Andromeda novæcæsareæ Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 181.
Andromeda novæcæsareæ Berry, idem, vol. 34, 1907, p. 204.

Description.—Leaves small, thick, and entire, with stout petioles and midribs and obscure secondary venation, which is immersed in the thick lamina. Length 2.5 to 5 centimeters. Width varies from 0.9 to 1.3 centimeters. Venation where visible shows numerous parallel, camptodrome, relatively long and thin secondaries which branch from the midrib at an acute angle. Though the majority of these leaves are equally acuminate at both ends, there is a great deal of variation in this respect, and a considerable number of specimens which are relatively broader, especially in the upper half, exhibit a well-marked tendency toward an obtusely rounded apex, in which the termination of the midrib shows as a small mucronate point. The base in these forms gradually narrows to the stout petiole. The variations in outline of this species are well shown in the figures reproduced in Newberry's monograph, the specimens from the southern Coastal Plain seeming to have more commonly than those from New Jersey an obtusely rounded apex.

In the Raritan formation this species is only known with certainty from the uppermost beds at South Amboy, N. J. It becomes more abundant in the overlying Magothy formation, occurring from New Jersey to Maryland in beds of this age. Farther south it is found as one of the typical fossils of the Black Creek formation in North Carolina, being a prominent but never abundant element in the dark lignitic laminated clays of the upper beds, associated with Araucaria, Cunninghamites, Pistia, and other genera, and with a marine fauna.

It also occurs in clays of the Middendorf member of the Black Creek formation of South Carolina and in the Tuscaloosa formation of Alabama, and was one of the few leaves which successfuly resisted maceration in the shallow shoreward deposits known as the Cusseta sand member of the Ripley formation of Georgia, occurring at Buena Vista in association with *Araucaria bladenensis* just as it does along Black River in North Carolina.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

ANDROMEDA GRANDIFOLIA Berry.

Plate XIV, figure 10.

Andromeda latifolia Smith, On the geology of the Coastal Plain in Alabama, 1894, p. 348.

Andromeda latifolia Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 120, Pls. XXXIII, figs. 6–8, 10 (non fig. 9); XXXIV, figs. 6–11; and XXXVI, fig. 10 (non Wright).

Andromeda latifolia Hollick, Bull. New York Bot. Garden, vol. 3, 1904, p. 416, Pl. LXXIX, fig. 3.

Andromeda latifolia Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 100, Pl. XXXIX, fig. 1.

Andromeda grandifolia Berry, Bull. Torrey Bot. Club, vol. 34, 1907, p. 204, Pl. XV, fig. 3.

Description.—Leaves thick and coriaceous, varying considerably in size and shape. From 4 to 20 centimeters in length by 1.5 to 7 centimeters in width. Ovate-lanceolate in outline, with an entire, usually somewhat undulate or unsymmetrical margin. Apex obtusely pointed or in some specimens rounded. Base somewhat wedge-shaped. Midrib and petiole very stout. Secondaries relatively few, six to eight pairs, stout and flexuous, branching from the midrib at an acute angle and sweeping upward in long curves, eventually inosculating to complete the strictly camptodrome venation.

This species occurs from the lower part of the Raritan formation of New Jersey to the top of the eastern leaf-bearing Cretaceous. It is a not uncommon fossil in the Magothy formation, the Black Creek formation of North Carolina, and the Tuscaloosa formation of Alabama. It is larger, relatively broader, and less regular than *Andromeda parlatorii* Heer, the two leaves figured on Plate XIV showing the average shape, with a length of about 10 centimeters and a width of about 5 centimeters.

Occurrence.—Middendorf arkose member of the Black Creek formation, Rocky Point, Sumter County. (Collected by L. F. Ward and L. C. Glenn.)

Collections.—U. S. National Museum.

ANDROMEDA EUPHORBIOPHYLLOIDES sp. nov.

Plate XIV, figure 7.

Description.—Leaves small, entire, obovate-lanceolate, with a broadly rounded apex and a narrowed cuneate base, about 5.3 centimeters in length by 1.25 centimeters in greatest width, which is in the apical half of the leaf. Petiole short and stout. Midrib stout. Secondaries numerous, approximately parallel, thin, branching from the midrib at acute angles, long, ascending, camptodrome. Texture coriaceous.

This species in its size, outline, and venation is referable to the genus Andromeda, greatly resembling some of the obovate leaves of the contemporaneous *Andromeda novæcæsareæ* Hollick, differing in its more elongate form and straighter, more produced base. It also resembles some of the leaves of the Dakota sandstone referred by Lesquereux[1] to his species *Eugenia primæva* but is more oblanceolate, with less full margins and straighter secondaries. It also resembles, especially in its general form, certain curious leaves described by Saporta from the Cenomanian of Portugal[1] and from the Turonian of France,[2] which are made the basis of a new genus, Euphorbiophyllum, and referred to the family Euphorbiaceæ.

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[1] The flora of the Dakota group: Mon. U. S. Geol. Survey, Vol. 17, 1899, p. 137, Pl. LIII, fig. 7.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

ANDROMEDA PARLATORII Heer.

Andromeda parlatorii Heer, Phyllites crétacées du Nebraska, 1866, p. 18, Pl. I, fig. 5.
Prunus ? parlatorii Lesquereux, Am. Jour. Sci., 2d ser., vol. 46, 1868, p. 102.
Leucothoe parlatorii Schimper, Paléontologie végétale, vol. 3, 1874, p. 11.
Andromeda parlatorii Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 112, Pl. XXXII, figs. 1 and 2.
Andromeda parlatorii Lesquereux, The Cretaceous flora, 1874, p. 88, Pls. XXIII, figs. 6 and 7, and XXVIII, fig. 15.
Andromeda parlatorii Heer, idem, vol. 6, Abth. 2, 1882, p.79, Pls. XXI, figs. 1b and 11, and XLII, fig. 4c.
Andromeda parlatorii Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 115, Pls. XIX, fig. 1, and LII, fig. 6.
Andromeda parlatorii Smith, On the geology of the Coastal Plain of Alabama, 1894, p. 348.
Andromeda parlatorii Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 120, Pls. XXXI, figs. 1-7, and XXXIII, figs. 1, 2, 4, and 5.
Andromeda parlatorii Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 420, Pl. XXXVII, figs. 1-4.
Andromeda parlatorii Berry, Bull. New York Bot. Garden, vol. 3, 1903, p. 97, Pl. L, figs. 1-4.
Andromeda parlatorii Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 79, Pl. I, figs. 1 and 2.
Andromeda parlatorii Berry, idem, vol. 33, 1906, p. 181.
Andromeda parlatorii Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 101, Pl. XXXIX, figs. 2-5.
Andromeda parlatorii Berry, Bull. Torrey Bot. Club, vol. 34, 1907, p. 203, Pl. XV, fig. 2.
Andromeda parlatorii Berry, Johns Hopkins Univ. Circ., new ser., No. 7, 1907, p. 81.

Description.—Leaves ovate-lanceolate in outline, with a long and gradually narrowed apex and a broad, somewhat rounded, but finally cuneate or slightly decurrent base. Petiole and midrib stout. Length about 10 to 12 centimeters. Width about 3 centimeters in the lower half of the leaf. Secondaries numerous, rather thin, subparallel, branching from the midrib at acute angles, long and ascending, at length camptodrome. Tertiaries mostly straight transverse. There is considerable variation in the size of these leaves and in the angle which the secondaries form with the midrib and consequently in their length and degree of curvature. Some of the specimens are much like the small leaves of *Andromeda grandifolia* Berry, but are not so slender nor so attenuated apically as the normal leaves of that species.

This species was first described by Heer in one of the earliest published accounts of the flora of the Dakota sandstone, and it has since been found to have a wide geographic range. It is one of the commonest fossils in the Dakota sandstone, having been recorded from Minnesota, Kansas, and Nebraska. In eastern North America it is recorded from the Atane beds of Greenland, the Raritan formation of New Jersey, the Magothy formation of Marthas Vineyard, New Jersey, Delaware, and Maryland, the Black Creek formation of North Carolina, and the Tuscaloosa formation of western Alabama.

In South Carolina this species has not been found in any abundance, a fact explained entirely by accidents of preservation.

The genus Andromeda of Linné has been much segregated by subsequent taxonomists, and this tendency to segregation is reflected in Schimper's proposal to refer this species to the genus Leucothoe. However, the more comprehensive name has obvious advantages for the paleobotanist where it is impossible to discriminate between the various ericaceous genera with any degree of accuracy.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley, Aiken County; Rocky Point, Sumter County (?). (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

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[1] Saporta, G. de, Flore fossile du Portugal, 1894, p. 218, Pl. XXXIX, fig. 23.

[2] Saporta, G. de, Évolution des Phanérogames, vol. 2, 1885, p. 117, fig. 125 C.

Order PRIMULALES.

Family MYRSINACEÆ.

Genus MYRSINE Linné.

MYRSINE GAUDINI (Lesquereux) Berry.

Plate XIV, figure 9.

Myrsinites ? gaudini Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 115, Pl. LII, fig. 4.

Myrsine elongata Hollick, Bull. Torrey Bot. Club, vol. 21, 1894, p. 54, Pl. CLXXVII, fig. 2.

Myrsine elongata Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 122, Pl. XXII, figs. 1–3.

Myrsine elongata Hollick, Annals New York Acad. Sci., vol. 11, 1898, p. 420, Pl. XXXVIII, figs. 3, 4b, and 4c.

Myrsine elongata Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 102, Pls. VIII, fig. 1b, and XXXIX, figs. 13 and 14.

Myrsine gaudini Berry, Bull. Torrey Bot. Club, vol. 36, 1909, p. 262.

Description.—Leaves oblanceolate or elongate-obovate in outline, 5.5 to 7 centimeters in length by 1.9 to 2.5 centimeters in greatest width. Margins entire. Apex obtusely rounded. Base somewhat elongated, narrowly cuneate. Petiole present, stout. Midrib stout below, abruptly diminishing in caliber. Secondaries numerous, eight to ten pairs, alternate, branching from the midrib at angles of 40° to 45°, camptodrome. When the tertiary venation is distinctly preserved, the venation is more typical of the genus than when only the secondaries are partly visible.

This species is well distributed in the Raritan formation and has been recorded also from Long Island and Staten Island. The identification of *Myrsinites? gaudini* Lesquereux with the eastern forms, with which it is obviously identical, extends the range eastward from Kansas to Long Island. It may be readily distinguished from the other species of Myrsine by its relatively narrow, elongated form. It is present in the Black Creek formation of North Carolina and the Tuscaloosa formation of Alabama. It is not abundant in the South Carolina Cretaceous, being present only in Aiken County. The figured specimen is typical and extremely close to the type, being a trifle more elongated, as are also the leaves of this species from the northern Atlantic Coastal Plain.

Occurrence.—Middendorf arkose member of Black Creek formation, near Langley, Aiken County. (Collected by L. W. Stephenson and E. W. Berry.)

Collections.—U. S. National Museum.

Order EBENALES.

Family EBENACEÆ.

Genus DIOSPYROS Linné.

DIOSPYROS PRIMÆVA Heer.

Plates XI, figure 3, and XIV, figures 12 and 13.

Diospyros primæva Heer, Phyllites crétacées du Nebraska, 1866, p. 19, Pl. I, figs. 6 and 7.

Diospyros primæva Heer, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 80, Pl. XVIII, fig. 11.

Diospyros primæva Heer, idem, vol. 7, 1883, p. 31, Pl. LXI, figs. 5a, 5b, and 5c.

Diospyros primæva Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 109, Pl. XX, figs. 1–3.

Diospyros primæva Smith, On the geology of the Coastal Plain of Alabama, 1894, p. 348.

Diospyros primæva Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 124, Pl. XXX, figs. 1–5.

Diospyros primæva Knowlton, Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 7, 1901, p. 317, Pl. XXXIX, fig. 3.

Diospyros primæva Berry, Bull. Torrey Bot. Club, vol. 32, 1905, p. 46, Pl. II.

Diospyros primæva Berry, idem, vol. 34, 1907, p. 204.

Diospyros primæva Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey vol. 50, 1907, p. 103, Pl. XL, figs. 2 and 11.

Description.—Leaves oblong-ovate in outline, variable according to age, ranging from 3 to 15 centimeters in length by 1.3 to 5 centimeters in greatest width, which is in the middle part of the leaf. Apex acute or obtuse. Base cuneate. Margins entire. Petioles rather long and very stout. Midrib also stout. Secondaries branching from the midrib usually at acute angles, subopposite or alternate, parallel, camptodrome. Tertiaries forming polygonal areoles, whose relative prominence is one of the features of this species.

This species, which is quite suggestive of the modern *Diospyros virginiana* Linné, was described by Heer from the Dakota sandstone of Nebraska nearly half a century ago. It has proved to be a most wide-ranging form, having been identified at both the Atane and Patoot horizons in Greenland; from various localities within the Dakota sandstone, and its probable southern equivalent the Woodbine sand of Texas; and, besides the fragments from Marthas Vineyard and Long Island, which are of questionable identity, it is common in either the Raritan or Magothy or homotaxial formations from New Jersey to Alabama. It has been recorded from the Cenomanian of Saxony and the Turonian of Bohemia.

Its most marked character is the prominence of its tertiary areolation. This species is common at all leaf-bearing horizons in the South Carolina Cretaceous deposits, and the material gathered near Langley is notable for the large number of small leaves associated with those of normal size. These conform to the type in all respects except that they are more slender and acuminate, a feature to be expected in the small leaves of Diospyros, and it is believed that they are not distinct from the type. Two of these small leaves are figured, the normal-sized leaves having been amply illustrated by Newberry.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County; near Langley, Aiken County; Rocky Point, Sumter County; right bank of Congaree River, about 25 miles below Columbia, Lexington County (?). (Collected by L. W. Stephenson, E. W. Berry, Earle Sloan, B. L. Miller, and M. W. Twitchell.)

Collections.—U. S. National Museum.

DIOSPYROS ROTUNDIFOLIA Lesquereux.

Plate XIV, figure 14.

Diospyros rotundifolia Lesquereux, The Cretaceous flora, 1874, p. 89, Pl. XXX, fig. 1.

Diospyros rotundifolia Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 112, Pl. XVII, figs. 8–11.

Diospyros rotundifolia Berry, Ann. Rept. State Geologist, New Jersey, for 1905, 1906, p. 139.

Diospyros rotundifolia Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 181.

Description.—Leaves entire, of various sizes, 4 to 10 centimeters in length by 2 to 7 centimeters in greatest width, which is in the middle part of the leaf. Outline broadly oval or elliptical. Apex broadly rounded. Base similar or somewhat narrowed and pointed. Petiole and midrib stout. Secondaries, six or seven pairs, branching from the midrib at angles of 50° to 60°, arched, camptodrome. Texture subcoriaceous. Venation less prominent than in *Diospyros primæva* Heer.

This species is a characteristic element in the post-Raritan flora of the Atlantic Coastal Plain, although at times liable to be confused with *Myrsine borealis* Heer or with some of the smaller, more orbicular, entire leaves of Populus. The venation is markedly different, however.

It was originally described from the Dakota sandstone of Kansas and is common in the Magothy formation in New Jersey, Delaware, and Maryland. It has also been recorded from the Tuscaloosa formation in western Alabama. In South Carolina it has been found only at the Rocky Point locality. The material, though complete, has the venation mostly opposite, and it is possible that it may represent some orbicular leguminous leaflet instead of this species, with which, however, it agrees admirably.

Occurrence.—Middendorf arkose member of Black Creek formation, Rocky Point, Sumter County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

DICOTYLEDONÆ INCERTÆ SEDIS.

Genus CALYCITES Auct.

CALYCITES MIDDENDORFENSIS sp. nov.

Plate X, figure 4.

Description.—Calyx-like organism, with a small central disk or receptacle from which radiate five linear, apically rounded, equidistant sepals, measuring 1.1 centimeters in diameter from tip to tip. Sepals slightly narrowed proximal, 1 millimeter or a fraction more in width.

Remains of this sort are commonly referred to the form genus Calycites, as the botanic affinity of but few specimens can be determined. A considerable number of species of Calycites have been described, coming from the Raritan, Magothy, and Dakota formations. It may be questioned whether forms like those described from the Magothy of Marthas Vineyard and Long Island by Hollick should not receive some other names, for they hardly represent calices, but are obviously fruits comparable with certain modern Dipterocarpaceæ or Hippocrateaceæ. The present species is based on the single complete specimen figured.

Occurrence.—Middendorf arkose member of Black Creek formation, near Middendorf, Chesterfield County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

BOTANIC CHARACTER OF THE FLORA.

The Cretaceous flora of South Carolina as made known in the present contribution consists of 76 species, distributed among 49 genera in 36 families and 26 orders. There are represented 1 member of the phylum Thallophyta, 2 of the Pteridophyta, and 73 Spermatophyta, including 14 Gymnospermæ (1 Cycadales and 13 Coniferales) and 59 Angiospermæ (5 Monocotyledonæ and 54 Dicotyledonæ). The largest orders are the Urticales, Ranales, Thymeleales, and Sapindales, each of which has 6 species.

The largest single genus is Ficus, which is represented by 5 species, and this genus is also the most abundant individually. The genera Salix, Magnolia, and Andromeda have 4 species each; Araucaria, Celastrophyllum, and Eucalyptus have 3 each; and the following genera are represented by 2 species each: Myrica, Quercus, Proteoides, Leguminosites, Laurus, Laurophyllum, Cinnamomum, and Diospyros.

Fossil plants are very unequally represented at the 11 localities enumerated, the locality near Middendorf furnishing 42 species, whereas the locality on Black Creek below Williamsons Bridge (3.9) has furnished no positively identified forms. The bulk of the described species have come from the Middendorf arkose member of the Black Creek formation, identifiable remains being uncommon in other deposits of the Black Creek formation, although lignites, fragmentary leaves, and comminuted vegetable matter are universally distributed throughout the typical Black Creek deposits and are relatively rare in the Middendorf member. This condition is due to a certain extent to the distribution of vegetation on the near-by land and more largely to what may be termed the accidents of preservation and is paralleled by the distribution of the plants in the Black Creek formation of North Carolina, where most of the forms come from the single favorably situated locality at Courthouse Bluff on Cape Fear River. In the more distinctly marine sedimentation, more remote from the shore or from Cretaceous islands, the plant remains were much macerated and triturated before entombment. For this reason a better idea of the flora as a whole and of the accompanying physical conditions can be obtained from the Middendorf flora, of which the general botanic bearing is equally applicable to the typical Black Creek flora, although the latter indicates somewhat different ecologic grouping and considerably different conditions of deposition.

After a brief statement of the character of the South Carolina Cretaceous flora as a whole, an effort will be made to picture the environmental factors—ecologic, topographic, climatic, and edaphic—which may legitimately be deduced from the plant assemblages found fossil in the Middendorf member and the typical Black Creek deposits.

The flora as a whole furnishes a single thallophyte, which is represented by poorly preserved remains of a dichotomously branched thallus of undetermined botanic affinity. It is confined to the Black Creek formation in South Carolina, but occurs rather more abundantly at the same horizon in North Carolina and also in the Magothy flora of Maryland; it indicates marine sedimentation.

The Pteridophyta are represented by one species each of Onoclea and Lycopodium, and strangely enough both are fruit-bearing specimens, the Lycopodium closely resembling the existing members of the genus and heretofore not being certainly known from the Mesozoic. The botanic affinity of the Onoclea is not conclusively determinable, although the remains represent a type found also in the Magothy formation and in the Upper Cretaceous of Greenland.

The Cycadales are represented by a single species of Podozamites, which is confined to the Middendorf member in South Carolina, but which occurs in the Black Creek formation of North Carolina, northward to New Jersey, in the Dakota sandstone of the West, and in Europe. The remains are detached leaflets of the type usually referred to Podozamites, although the botanic affinity of many of these leaflets is not fully established.

The Coniferales are well represented. The Taxaceæ are recognized by the Cephalotaxus-like fruits which are so common in the Black Creek formation of North Carolina and which occur also in the upper part of the Tuscaloosa formation of Alabama. The other member of this family is referable to the curious fernlike genus Protophyllocladus, a characteristic Upper Cretaceous type widely distributed in North America. The species is new but occurs also in the Magothy formation of Maryland.

The Araucariaceæ, abundant in the Mesozoic though antipodean in existing flora, have three species of typical araucarias—one based on foliage, another on cone scales, and the third on seeds—but it is quite probable that all may belong to a single botanic species. The other family in this order, the Brachyphyllaceæ, is represented by the characteristic and widely distributed *Brachyphyllum macrocarpum* Newberry, which ranges from the Raritan to the Montana and which is the last survivor of a common older Mesozoic type of plant.

The Pinaceæ are represented by a species of Pinus of modern aspect and by the characteristic remains of the wide-ranging and widely distributed *Sequoia reichenbachi* (Geinitz) Heer, a species whose Raritan representative Hollick and Jeffrey propose to refer to the Araucariaceæ, although it may be noted that their argument is inconclusive. Furthermore, it seems probable that all of the forms referred to this species may not be identical. The modern oriental genus Cunninghamia is doubtfully represented by a species of Cunninghamites, which is quite widely distributed and which ranges from the Cenomanian to the Senonian abroad and probably as widely in this country. The genus Moriconia is abundantly represented in the Middendorf member, its most southerly known occurrence. From this region it ranges northward, a closely allied species occurring both in Greenland and in Europe.

The Cupresseaceæ are certainly represented by *Widdringtonites subtilis* Heer, a form which ranges from the Atane beds of Greenland southward along the Atlantic coast to Alabama. Rather characteristic, apparently four-valved cones of the Widdringtonia (Callitris) type are associated with the foliage in clays of the Middendorf member. In the Tuscaloosa formation of western Alabama this species is very common and has furnished a number of specimens with the cones attached to the leafy twigs of this type, so that the botanic affinity of this species seems to be established beyond dispute. In addition to the foregoing forms of more or less certain botanic relationship a cone is described from the Black Creek formation and a cone scale from the Middendorf member, both of unknown affinity.

The Monocotyledonæ have furnished five species, a Potamogeton, an Arundo, a Phragmites, and a Carex, waterside types whose occurrence as fossils are easily explained, as well as fragmentary remains of a large palmetto-like fan palm, Sabalites, one of the earliest known occurrences of a plant of this type. Palms appear simultaneously in the early part of the Upper Cretaceous in both Europe and America, and before its close they appear to have become numerous and diversified as well as widely distributed.

Of the Dicotyledonæ, the amentiferous families are represented by nine species. The Juglandales have a species of Juglans which ranges from Greenland to Georgia.

The Myricales have two characteristic species of Myrica, a genus of considerable importance in Upper Cretaceous floras everywhere and in more recent floras as well. The willows have four species, one peculiar to the Middendorf member and three widely distributed in beds of this or nearly the same age. The oaks have furnished two species, both clearly defined. It is singular that the oaks appear in such abundance both in this country and Europe soon after the dawn of the Upper Cretaceous. They afford one of the marks of post-Raritan floras in the Atlantic Coastal Plain.

The Urticales form one of the most abundant orders in the South Carolina Cretaceous—in point of numbers of individual specimens easily the most abundant. A single doubtful species is referred to the modern warm-temperate genus Momisia, which, except for a species recently described by the writer from the Eocene of Georgia, is unknown in the fossil state. The figs number five species, including four species with lanceolate leaves and pinnate venation and one species with shorter and broader leaves and palmate venation. One of the lanceolate figs, *Ficus stephensoni*, is new, although it occurs in North Carolina; the others are all well known and large forms of wide distribution. They are exceedingly abundant in South Carolina; both *Ficus crassipes* Heer and *Ficus krausiana* Heer occur at four localities at least and are very common at certain of these, particularly in the clay ironstones at Rocky Point. One of the few contrasts to be noted in tracing this Upper Cretaceous flora southward from Greenland is the tendency shown by a number of forms toward the development of prolonged attenuated tips. This is prominently shown in these species of Ficus, both here and in the Tuscaloosa flora of Alabama, and it has been interpreted as indicating a heavier rainfall and more humid climate than in higher latitudes. This peculiarity is not confined to the genus Ficus, but is shared by a number of other genera belonging to these floras.

Of the Proteales, the Proteaceæ, at present largely and almost exclusively developed in the Southern Hemisphere, are represented by two species of Proteoides, so called from their close affinity with the modern species of Protea. Many botanists, notably in England, have questioned such identifications, especially as made by Ettingshausen and others in studies of the Tertiary floras of Europe. Most of these identifications have a large element of certainty, however, and are paralleled and confirmed by the similar Cretaceous range and modern restriction of a large number of unrelated genera. The present place is unsuitable for controversial matter, but the writer will say that rather extensive distributional studies have served in a large measure to confirm the presence in the Cretaceous floras of North America of species of Proteaceæ, Myrtaceæ, and other types.

The order Ranales, which at the present time has received such undue prominence through the phylogenetic speculations of Wieland and Arber, is represented by six species—a Dewalquea of remarkable and striking appearance, common to the Middendorf member and to the Tuscaloosa formation of Alabama; a new species of Illicium; and four well-known species of Magnolia, two of which range northward as far as Greenland and three southward into Alabama. Magnolias are common everywhere in Upper Cretaceous floras from Greenland to Alabama.

The order Rosales has no very definite or remarkable representatives in the South Carolina Cretaceous. A form doubtfully identified as Hamamelites occurs at Rocky Point, and two leaflets are referred to Leguminosites, one as a Cæsalpinia, and one as an Acacia-like form.

The order Geraniales, though poorly represented, contains two remarkable forms, a Citrophyllum very close to the modern genus Citrus, which ranges northward as far as New Jersey, and Crotonophyllum, a genus allied to the modern genus Croton of the Euphorbiaceæ. Crotonophyllum is rather common in the Middendorf member, the only other species of the genus being a Cenomanian form from Bohemia.

The order Sapindales is a large one, represented by six species—one a Sapindus, one a form doubtfully referred to the genus Pachystima, one a large Rhus, and three species of Celastrophyllum. The last genus becomes abundant at the close of the Lower Cretaceous, with seven species in the Patapsco formation. There are no less than nine species in the Raritan formation, but this number is reduced to two in the Magothy, two in the Black Creek, and three in the Middendorf member. Celastrophyllum is unrepresented in the Montana flora of the West.

The order Thymeleales also includes six species, of which two are well-known species of Laurus, two are species of Laurophyllum confined to this horizon in the Atlantic Coastal Plain, and two are species of Cinnamomum, one being the widespread *Cinnamomum newberryi* Berry and the other new.

The order Myrtales has three species of Eucalyptus, all close to modern species. This is particularly true of *Eucalyptus angusta* Velenovsky, which is also associated with typical Eucalyptus fruits in the Cenomanian of Europe.

The order Umbellales is represented by a single species of Hedera, a form of wide distribution. The Araliaceæ, so common in homotaxial American floras, have not been detected in either the Middendorf member or other deposits of the Black Creek formation in South Carolina, though a single Aralia is found in the Black Creek formation of North Carolina and several species appear in the Tuscaloosa and Magothy formations.

The order Ericales has four species of Andromeda, one new and the other three widespread in deposits of this or nearly the same age in the Atlantic Coastal Plain.

The Primulales are represented by a single rather widespread species of Myrsine and the Ebenales by two species of Diospyros, one the relatively large-leaved *Diospyros primæva* of Heer, which ranges from Greenland to Alabama in eastern North America and from Kansas and Nebraska to Texas in the interior, and which is exceedingly common in the South Carolina Cretaceous; and the other the less common *Diospyros rotundifolia* Lesquereux of the Dakota sandstone and the Magothy formation. These leaves are certainly allied to the modern Diospyros and are associated in the Raritan formation of Maryland with characteristic fruit calices scarcely distinguishable from those of certain modern species.

PHYSICAL CONDITIONS INDICATED BY THE FLORA.

An effort to picture accurately the environment of a fossil flora is beset with unusual difficulties, as may be readily imagined, and these difficulties increase in geometric ratio to the time that has elapsed since it existed in life. Furthermore, the science of plant ecology is so recent in development that the data with which to compare fossil floras are very inadequate. Particularly is this true of the existing floras of the tropical and subtropical zones with which the Cretaceous flora is most naturally compared. The strand flora of the tropics is fairly well known, but of inland and upland floras over wide areas practically no information is available, although the Philippine Forest Service has made a most laudable beginning in this direction.

For this reason the discussion which follows probably merits more or less criticism, especially of the statements where the writer has endeavored to particularize. An effort has been made, however, to avoid purely speculative points, and it is believed that the more general statements regarding climate and other conditions of growth will stand, whatever may be the fate of the details.

As has been shown, the sediments and their contained floras indicate shallow seas and a considerable elevation and relief of the Piedmont area. River gradients were high and the streams numerous and more or less torrential in character. In the early part of the period coastal sounds or bays were present, but these were subsequently submerged and the coast line appears not to have been subsequently broken by any large reentrants, although part of the strand flora was probably a swamp flora and swamps were also present in the lower courses of the streams, especially in the later half of the period. With regard to the climatic conditions the Cretaceous floras are to a certain extent unlike those of later periods and are so far removed from the present that no very precise conclusions are possible. It is safe to assume that the climate was mild, however, for the plant grouping clearly shows this. Seasonal changes were not strongly marked, as is shown by the lack of periodic alterations (growth rings) in the petrified and lignitized woods. These have not been critically studied, nor are they included in the systematic account of the flora, but they have been examined sufficiently to corroborate the foregoing statement. That the climate was not tropical in character may be assumed from the manner in which this flora preserves its integrity when traced northward over many degrees of latitude. It is essentially a unit from Alabama to New Jersey, and preserves even in its far northern occurrence on the west coast of Greenland—though differences are perceptible—a facies remarkably similar. Even in Greenland this flora has nearly as many species which in modern floras are customarily associated with the warmer temperate and subtropical zones as in its most southerly occurrence. We may confidently assert that frosts were unknown. The trees were not all evergreen, although some were, and the leaves, from the manner in which they are found fossil, were apparently shed at maturity and not seasonally. It is believed that insolation, or the pseudoxerophytism of swamp habitats, rather than any approach to aridity, explains the presence of numerous coriaceous-leafed forms, such as the four species of Andromeda, and the abundance of Leguminosæ and of gymnosperms, many of them having reduced leaves like Brachyphyllum, Moriconia and Widdringtonites, or developing phylloclads as in the Protophyllocladus of the Middendorf member or Androvettia of the homotaxial beds of the Black Creek formation in North Carolina and the Eutaw formation in Georgia.

Sequoia in the existing flora thrives only in a belt fed by the moisture-laden winds from the Pacific. As a fossil it is excessively abundant in the Middendorf member and, in fact, in all post-Raritan deposits of the Atlantic Coastal Plain Cretaceous which furnish any flora. That the Cretaceous rainfall was plentiful may be inferred not only from the species of plants preserved, but also from the formation of dripping points on various leaves, this feature being especially emphasized in the Tuscaloosa flora of Alabama. Judged by the facts of the present-day geographic distribution of plants, the flora as a whole presents an antipodean facies with its species of Eucalyptus and Proteoides and its abundant Araucariaceæ, but this is only another way of emphasizing its Mesozoic character, for the abundant evidence at our command shows that all these types were practically cosmopolitan in the Mesozoic. Another feature which appears strange to modern plant geographers is the curious mingling of forms which in the existing flora are to a greater or less extent climatically segregated. Willows and walnuts growing with figs, eucalyptus, laurels, and araucarias would indeed be anomalous in the present flora, but these and similar associations are familiar enough in fossil floras, not only during the Mesozoic but well into the Cenozoic.

Even though no close comparisons with modern ecologic groups are possible, it would seem that if the Upper Cretaceous flora were existing at the present time it would be included by ecologic botanists under that somewhat elastic head which Schimper calls "temperate rain forests." In no other modern plant associations do we find that commingling of temperate and tropical types that we find in certain present-day temperate rain forests, as, for example, those of southern Chile, southern Japan, Australia, and New Zealand. In the last-named locality Aralia, Laurus, Cinnamomum, Magnolia, and Sterculia are associated with Quercus, Fagus, Gleichenia, Dryopteris, and Dicksonia. In some respects the flora of New Zealand is more tropical in its facies and more like our eastern Upper Cretaceous floras than any other now existing. In New Zealand conifers are abundant and include forms with reduced leaves like Libocedrus and Dacrydium, as well as forms with broad leaves like Dammara, Podocarpus, and Phyllocladus. Dicotyledonæ are numerous and varied, including between 100 and 150 species, among which forms of Myrtaceæ, Lauraceæ, and Proteaceæ, with coriaceous leaves, are prominent. The undergrowth is rich in tree ferns and various genera of Araliaceæ.

When this modern flora is compared element for element with the Coastal Plain Cretaceous flora many differences naturally become apparent; nevertheless, the resemblance between the two is remarkable. In the Upper Cretaceous flora of the Coastal Plain the narrow or scale-leafed conifers are represented by Sequoia, Moriconia, Brachyphyllum, and Widdringtonites. Dammara represents the broad-leafed araucarias; Androvettia and Protophyllocladus represent the modern Phyllocladus. The Dicotyledonæ are numerous and varied; temperate and tropical types are mixed, and there are numerous coriaceous forms belonging to a number of the same families as in the New Zealand flora. Aralias are common in both floras.

That the physical conditions approximated the foregoing outline is further indicated by the presence of many plants which normally grow in streams with considerable flow or along stream margins. There is an aquatic species, *Potamogeton middendorfensis*, which it is hard to imagine growing at sea level in the latitude of South Carolina during the Upper Cretaceous. There are two large-leafed grasses (Arundo and Phragmites) and a sedge, all strongly mesophytic types; four species of willow; and four thick-leafed laurels and two Cinnamomums, whose existing descendants flourish in humid localities, as do those of the numerous figs and magnolias. The figs are very abundant individually in the Middendorf member, especially at localities like that at Rocky Point. They are for the most part lanceolate-leafed forms and have developed to a greater or less extent long attenuated tips that are absent in the same species toward the northern limit of their range. These tips are commonly known as dripping points and are understood to indicate a considerable rainfall. They are especially noticeable in the South Carolina representatives of *Ficus crassipes* Heer. It is believed that these figs found their optimum conditions in the coastal swamps and extended from them up the river valleys to the amphitheaters toward the heads of streams, though they were not confined to such situations, as is proved by their wide geographic distribution at this time. In similar situations grew the broad-leafed gymnosperms, the palms, the entire-leafed *Quercus sumterensis*, and the various species of Proteoides, Illicium, Eucalyptus, Diospyros, Cinnamomum, Citrophyllum, Laurus, and Magnolia. The flora of the typical Black Creek deposits of South Carolina is so scanty, embracing only 17 species, that it does not in itself furnish adequate data for an attempt to picture its environment. When supplemented by the Black Creek flora of North Carolina somewhat more data are provided, but still the material is insufficient for the purposes mentioned. The occurrence of obscure remains of a marine alga, present also in North Carolina and in the Magothy of Maryland, may be noted as indicative of the presence of the sea or at least of brackish water. Lignite and amber are common, also the remains of Araucaria, Cephalotaxus-like fruits, Eucalyptus, Ficus, Myrica, and similar forms. The flora is mixed, including upland types which must have made perhaps very considerable river journeys before fossilization. Strand and swamp plants are also present, and coriaceous forms predominate, owing to their survival in agitated waters which destroyed the more delicate plant remains. The character of the fossils is a clear indication that the bays or sounds, which had been present in at least a part of the area during Middendorf time, had disappeared, and the Coastal Plain lacked large estuaries which usually afford such admirable means for fossilization. We may therefore infer that the coast line was unbroken, or that if there were estuary plant beds they have been destroyed by the erosion of the landward margin of the deposits or are not exposed at the present time. The differences in the flora between the early Middendorf and late Black Creek were probably not considerable, and physical conditions were not very dissimilar. The land had approached sea level and the ground water would be nearer the surface. The climate probably underwent no appreciable change, and the rainfall and humidity were still ample, although the writer is inclined to think that the rainfall was somewhat diminished. The natural radiation of the individual species in the floras doubtless caused great changes in distribution, and other changes were doubtless due to the fact that the area was in the direct line of migration between the north and the south, but sufficient data to illustrate these various changes have not yet been accumulated.

CORRELATION OF THE BLACK CREEK FORMATION.

In considering the correlation of the Middendorf member and the other Black Creek deposits the first question to be decided is the relation which they bear to each other. Though the writer's position on this point may be inferred from what has gone before, a few comments are necessary, as at first sight the floras apparently show considerable differences.

Of the 76 species described in the foregoing pages, 62 come from the Middendorf member and 17 from the other deposits of the Black Creek formation. Of these 76 species the following are described as new:

Acaciaphyllites grevilleoides.
Algites americana.
Andromeda euphorbiophylloides.
Araucaria darlingtonensis.
Calycites middendorfensis.
Celastrophyllum carolinensis.
Cinnamomum middendorfensis.
Crotonophyllum panduræformis.
Ficus celtifolius.
Heterolepis cretaceus.
Illicium watereensis.
Leguminosites middendorfensis.
Lycopodium cretaceum.
Momisia carolinensis.
Pachystima? cretacea.
Potamogeton middendorfensis.

Proteoides parvula.
Protophyllocladus lobatus.
Quercus sumterensis.
Quercus pseudowestfalica.
Rhus darlingtonensis.
Sabalites carolinensis.
Salix sloani.
Strobilites anceps.

Although these new species are of slight value in exact correlation, their evidence is entirely in accord with that deduced from the remainder of the flora. The bulk are from the Middendorf member, only *Algites americana*, *Araucaria darlingtonensis*, *Rhus darlingtonensis*, and *Strobilites anceps* coming from the other Black Creek deposits. Extensive collections from all parts of the Coastal Plain are undergoing elaboration by the writer, who, since the original description in manuscript, has identified *Algites americana* from the Black Creek formation of North Carolina and from the Magothy formation of Maryland, and *Protophyllocladus lobatus* from the Magothy of Maryland. *Araucaria darlingtonensis* has been shown to be closely allied to the other Black Creek araucarias, and *Andromeda euphorbiophylloides*, in all probability, occurs on the border between the Tuscaloosa and the Eutaw in Hale County, Ala. *Quercus pseudowestfalica* is now known to occur in the Black Creek formation of North Carolina, and the Sabalites is seen to be close to *Sabalites magothiensis* Berry from the Magothy formation of the northern Coastal Plain from New Jersey to Maryland. The genera Crotonophyllum and Illicium are most closely related to species described from the Cenomanian of Bohemia. None of the genera occur in the Montana flora of the west except Ficus and Salix, genera present from the Raritan to the Recent.

Only the following species are common to the Middendorf member and other deposits of the Black Creek formation in the South Carolina area:

Ficus krausiana Heer.
Laurophyllum nervillosum Hollick.
Proteoides lancifolius Heer.
Salix lesquereuxii Berry.

Although this seems a very small common element, all the forms are typical of this stage of the Cretaceous, and all except Proteoides are especially characteristic of the Magothy, Black Creek, and Tuscaloosa floras. The identity of the Middendorf and other Black Creek floras is greatly strengthened when comparisons are made with the latter flora as developed in the North Carolina area, the result showing 27 species common to the two formations.

The following Middendorf species which have not been found in the other Black Creek deposits of South Carolina occur in beds of Black Creek age in North Carolina:

Andromeda grandifolia Berry.
Andromeda novæcæsareæ Hollick.
Andromeda parlatorii Heer.
Araucaria jeffreyi Berry.
Brachyphyllum macrocarpum Newberry.
Celastrophyllum crenatum Heer.
Cinnamomum newberryi Berry.
Citrophyllum aligerum (Lesquereux) Berry.
Cunninghamites elegans (Corda) Endlicher.
Diospyros primæva Heer.
Eucalyptus geinitzi (Heer) Heer.
Ficus crassipes Heer.
Ficus krausiana Heer.
Ficus stephensoni Berry.
Juglans arctica Heer.
Laurophyllum elegans Hollick.
Leguminosites robiniifolia Berry.
Magnolia capellinii Heer.
Moriconia americana Berry.
Myrsine gaudini (Lesquereux) Berry.
Phragmites pratti Berry.
Pinus raritanensis Berry.
Podozamites knowltoni Berry.
Quercus pseudowestfalica Berry.
Salix flexuosa Newberry.
Salix lesquereuxii Berry.
Sequoia reichenbachii (Geinitz) Heer.

The following species occur in the Middendorf member but have not been detected in the other Black Creek deposits, either in North or South Carolina:

Acaciaphyllites grevilleoides Berry.
Andromeda euphorbiophylloides Berry.
Arundo grœnlandica Heer.
Cæsalpinia middendorfensis Berry.
Calycites middendorfensis Berry.
Carex clarkii Berry.
Celastrophyllum carolinensis Berry.
Celastrophyllum elegans Berry.
Cinnamomum middendorfensis Berry.
Crotonophyllum panduræformis Berry.
Dewalquea smithi Berry.
Diospyros rotundifolia Lesquereux.
Eucalyptus wardiana Berry.
Ficus atavina Heer.
Ficus celtifolius Berry.
Hamamelites? cordatus Lesquereux.
Heterolepis cretaceus Berry.
Illicium watereensis Berry.
Laurophyllum nervillosum Hollick.
Laurus atanensis Berry.

Laurus plutonia Heer.
Leguminosites middendorfensis Berry.
Lycopodium cretaceum Berry.
Magnolia tenuifolia Lesquereux.
Magnolia obtusata Heer.
Momisia carolinensis Berry.
Onoclea inquirenda (Hollick) Hollick.
Pachystima? cretacea Berry.
Proteoides parvula Berry.
Protophyllocladus lobatus Berry.
Potamogeton middendorfensis Berry.
Quercus sumterensis Berry.
Sabalites carolinensis Berry.
Salix pseudohayei Berry.
Salix sloani Berry.
Sapindus morrisoni Heer.
Widdringtonites subtilis Heer.

These include 17 new species thus far confined to the Middendorf member and without value in close correlation. Of the remaining 21 species with a wider distribution 4 occur in the Raritan of New Jersey, 6 in the Tuscaloosa formation, the large number of 15 in the Magothy formation, 8 in the Dakota sandstone, and 9 in the Greenland Cretaceous. This illustrates very well the remarkable unity of this flora from Greenland to Alabama, and also indicates conclusively the practical synchroneity between the Middendorf member and the other deposits of the Black Creek formation of South Carolina.

A similar relationship is shown by the following list of North Carolina Black Creek species which have not been detected in either the Middendorf member or the other Black Creek deposits in the South Carolina area:

Acerates amboyense Berry.
Androvettia carolinensis Berry.
Araucaria clarki Berry.
Celastrophyllum undulatum Newberry.
Cinnamomum heerii Lesquereux.
Cornophyllum sp.
Cycadinocarpus circularis Newberry.
Dammara borealis Heer.
Dewalquea groenlandica Heer.
Eucalyptus attenuata Newberry.
Eucalyptus linearifolia Berry.
Ficus ovatifolia Berry.
Ficus daphnogenoides (Heer) Berry.
Gleditsiophyllum triacanthoides Berry.
Kalmia brittoniana Hollick?
Liriodendron dubium Berry.
Liriodendron cf. primævum Newberry.
Malapoenna horrellensis Berry.
Myrica cliffwoodensis Berry.
Myrsine borealis Heer.
Phaseolites formus Lesquereux.
Pisonia cretacea Berry.
Pistia nordenskioldi (Heer) Berry.
Planera cretacea Berry.
Pterospermites carolinensis Berry.
Pterospermites crednerafolia Berry.
Quercus pratti Berry.
Salix newberryana Hollick.
Salix eutawensis Berry.
Sassafras acutilobum Lesquereux.
Sequoia heterophylla Velenovsky.
Sequoia minor Velenovsky.
Tumion carolinianum Berry.

Here again the species which are not confined to North Carolina are mingled in other homotaxial deposits, such as those of the Magothy formation of the North Atlantic Coastal Plain or the Tuscaloosa formation of Alabama, with the previously enumerated forms not common to the described floras of the two States.

The conclusion seems incontrovertible that in correlation the Middendorf member and the typical Black Creek may be considered as a unit, and that within the State they confirm the field observations that the stratigraphic sequence comprises initial Middendorf sedimentation of short duration, contemporaneous Middendorf and typical Black Creek sedimentation, especially when the Peedee and Aiken areas are compared, and finally typical Black Creek sedimentation only for a considerable period. When the flora as a whole is compared with outside areas it is brought out that 32 of the species in the Black Creek formation of North Carolina are of admitted identity in South Carolina and that 26 species occur either in the Tuscaloosa formation of Alabama or the Eutaw formation of Georgia. It seems to the writer that the synchroneity between these beds and the upper part of the Alabama Tuscaloosa and the lower portion of the Eutaw must be admitted, for the close similarity in their floral characteristics is corroborated by similar lithologic characters. It is believed, however, that the lower part of the Tuscaloosa of western Alabama is older than any Upper Cretaceous of the eastern Gulf or Atlantic Coastal Plain as far north as the New Jersey-Maryland area, where the uppermost Raritan is to be considered contemporaneous with it, the rest of the Raritan formation being still older. With the Magothy flora of the northern Coastal Plain, the Middendorf flora has 35 species in common, or about 50 per cent of its total flora. That the two floras are essentially a unit seems certain. In the New Jersey area the Magothy flora is confined to the transitional beds lying above the Raritan formation and at the base of the marine series of deposits, whereas in the southern and Gulf coastal plains similar fossil plants occur in lenses or in beds interstratified with marine fossiliferous beds. This shows that the southern representative of the Magothy flora was contemporaneous with the southern representative of the Matawan fauna and makes it probable that the Magothy flora in the New Jersey-Maryland area persisted through Matawan time. The Matawan formation has yielded only one or two fossil plants—a Ficus in the clays of Woodbury, N. J., and a Dammara in Maryland—and in both areas these species occur in the Magothy formation also.

The Black Creek flora contains 17 species found in the Atane beds of Greenland and 9 found in the Patoot beds. In the Cenomanian of Europe 9 of its species are found, in the florally unfossiliferous Turonian 1 species, and in the Senonian 4 species.

The eastern Cretaceous floras above the Raritan, possibly including those of the uppermost Raritan, correspond with the flora usually known as that of the Dakota sandstone. The rocks containing them are conformably overlain by deposits carrying a marine fauna but very few fossil plants. There are 23 species common to the South Carolina Cretaceous and the Dakota sandstone. The Black Creek formation of North Carolina, out of a total of 66 species, has 20 species in common with the Dakota. The Montana group flora is entirely unlike the eastern Cretaceous floras, having scarcely a single element in common. Certain stages in the evolution of the eastern Cretaceous flora can be made out, though in general the forms have a wide stratigraphic range. This is paralleled, however, by an almost equally wide stratigraphic range of the faunas.

To render intelligible to a wider circle of readers the results of the present discussion the probable European equivalents of these floras should be indicated, although it is admitted that attempted exact correlations between geologic formations on opposite sides of the Atlantic must always be more or less untrustworthy.

In Europe there are available for comparison abundant Cenomanian floras in Portugal, France, Germany, and especially in eastern Europe (Bohemia, Dalmatia, and other regions). The Turonian of Europe, on the other hand, is for the most part lacking in fossil plants, which become abundant again in the Senonian of Prussia, Saxony, and Bohemia. Our Dakota flora has always been considered Cenomanian; most paleozoologists have considered the Benton as Turonian (a view that is widely accepted in this country at the present time); and the Montana group has been uniformly considered as representing part of the Senonian. The Atlantic Cretaceous floras have been considered Cenomanian, and the associated and overlying faunas Senonian (exclusive of the Rancocas and Manasquan faunas of New Jersey, which have been justly considered Danian by Clark and others).

In the writer's opinion no Cenomanian floras are known in America, unless the Raritan flora and that of the Washita group of the Texas and southern Arkansas area represent that stage of European geology, and the post-Raritan floras of the East[1] are for the most part of Turonian age, as is also the major part, at least, of the Dakota flora of the West.[2]

The occurrence and range of the species of the South Carolina Cretaceous which form the partial basis of the foregoing discussion are fully set forth in the accompanying tables:

Approximate equivalents of the plant-bearing Cretaceous deposits of South Carolina.

South Carolina.	North Carolina.	Western Alabama.	New Jersey-Maryland.	Europe.
Marine Cretaceous (no known flora).	Marine Cretaceous (no known flora).	Marine Cretaceous (no known flora).	Marine Cretaceous (no known flora).	Emscherian.
				?
Black Creek.	Black Creek.	Eutaw.	Matawan (Marine, with no known flora).	Turonian.
Middendorf arkose member of Black Creek		Tuscaloosa.	Magothy.	
Hiatus.	Hiatus.	Hiatus.	Raritan.	Cenomanian.
Lower Cretaceous (no known flora).	Lower Cretaceous (no known flora).	Carboniferous.	Lower Cretaceous, Triassic, or crystalline rocks.	

---

[1] With the exception of the meager floras in the Ripley formation and its equivalents.

[2] Some paleontologists consider the Coastal Plain plant-bearing formations to be lower Senonian.

Distribution of Upper Cretaceous plants in South Carolina and their range elsewhere.

	Black Creek formation of South Carolina.										Raritan formation, New Jersey to Maryland.	Magothy formation, New Jersey to Maryland.	Black Creek formation, North Carolina.	Eutaw formation, Georgia and Alabama.	Tuscaloosa formation, Alabama.	Woodbine sand, Texas.	Dakota sandstone, western interior.	Montana Group, western interior.	Atane and Patoot beds, Greenland.	Cenomanian, Europe.	Turonian, Europe.	Senonian, Europe.
	Middendorf arkose member.																					
	Near Middendorf.	Rocky Point.	Congaree River.	Langley.	Miles Mill.	Below Cheraw.	Black Creek.	Cashua Road, Darlington.	Near Williamsons Bridge.	Ashby Place.												
Algites americana										×		×	×									
Onoclea inquirenda	×											×							×			
Lycopodium cretaceum	×														×							
Podozamites knowltoni		×									×	×					×					
Protophyllocladus lobatus		×										×										
Cephalotoxospermum carolinianum							?			×			×	×								
Araucaria bladenensis										×		×	×	×							?	
Araucaria darlingtonensis							×															
Araucaria jeffreyi				×									×	×								
Brachyphyllum macrocarpum	×										×	×	×				×			?		
Pinus raritanensis	×										×	×	×									
Sequoia reichenbachi	×										×	×	×	×	×		×	×	×	×	×	×
Cunninghamites elegans		×										×	×	×				×	×	×	×	×
Widdringtonites subtilis	×	×									×	×			×					×		
Moriconia americana	×											×	×									
Strobilites anceps							×															
Heterolepis cretaceus		×																				
Potamogeton middendorfensis	×																					
Arundo grœnlandica		×																	×			
Phragmites pratti		×											×	×								
Carex clarkii		×										×										
Sabalites carolinensis				×																		
Juglans arctica	×										×	×	×	×			×		×			
Myrica brittoniana									×			×	×									
Myrica elegans								×					×									
Salix flexuosa	×		×	×							×	×	×	×	×		×					
Salix lesquereuxii	×	×	×	×	×			×			×	×	×	×			×					
Salix pseudohayei	×										×											
Salix sloani				×	×																	
Quercus sumterensis		×																				
Quercus pseudowestfalica	×	×			×								×									×
Momisia carolinensis	×																					
Ficus atavina	×	×										×					×		×		×	
Ficus celtifolius	×																					
Ficus crassipes	×	×	×	×								×	×		×		×		×			
Ficus krausiana	×	×	×				×		×			×	×		×		×			×	×	
Ficus stephensoni	×			×									×									
Proteoides lancifolius	×	×						×									×					×
Proteoides parvula	×																					
Dewalquea smithi				×	×										×							
Magnolia capellinii (?)	×	×										×	×	×	×		×		×			
Magnolia newberryi (?)								×														
Magnolia obtusata	×											×			×		×		×			
Magnolia tenuifolia (?)	×											×					×					
Illicium watereensis		×																				
Hamamelites (?) cordatus		×															×					
Acaciaphyllites grevilleoides	×																					
Cæsalpinia middendorfensis	×																					
Leguminosites middendorfensis	×																					
Leguminosites robiniifolia				×									×									
Citrophyllum aligerum	×				×						×	×	×		×		×					
Crotonophyllum panduræformis	×	×		×	×																	
Sapindus morrisoni				×								×			×	×	×		×			
Pachystima (?) cretacea	×																					
Celastrophyllum elegans		×										×										
Celastrophyllum crenatum	×										×	×	×		×				×			
Celastrophyllum carolinensis				×																		
Rhus darlingtonensis								×														
Laurus plutonia	×			×							×	×			×	×	×		×	×		
Laurus atanensis		×							×			×					×		×			
Laurophyllum elegans	×										×	×	×									
Laurophyllum nervillosum	×							×			×											
Cinnamomum newberryi		×	×								×	×	×	×	×	×	×		×	?		
Cinnamomum middendorfensis	×																					
Eucalyptus angusta									×		×		×	×						×		
Eucalyptus geinitzi	×	×		×							×	×	×		×	×	×		×	×	×	
Eucalyptus wardiana (?)	×											×			×							
Hedera primordialis						×		×			×		×						×	×		
Andromeda novæcæsareæ	×										×	×	×		×	×						
Andromeda grandifolia		×									×	×	×		×							
Andromeda euphorbiophylloides	×																					
Andromeda parlatorii				×							×	×	×		×		×		×			
Myrsine gaudini				×							×	×	×		×							
Diospyros primæva	×	×	×	×	×						×	×	×		×	×	×		×	×	×	
Diospyros rotundifolia		×										×			×		×					
Calycites middendorfensis	×																					

PLATE II.

PLATE II.

Page.

FIGURES 1-6. *Lycopodium cretaceum* Berry, Middendorf 15
- 1. Large fruit spike.
- 2. Smaller fruit spike, × 5.
- 3. A single scale, × 10.
- 4. Diagrammatic ventral view of sporophyll, × 10.
- 5, 6. Diagrammatic view of sporophyll in median longitudinal section, × 10.

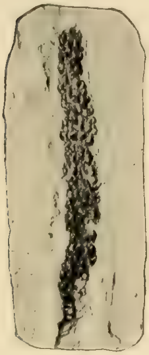
FIGURES 7, 8. *Onoclea inquirenda* (Hollick) Hollick, Middendorf 14

FIGURES 9-13. *Protophyllocladus lobatus* Berry, Rocky Point 17

FIGURES 14-17. *Widdringtonites subtilis* Heer, Middendorf 25
- 14, 15. Cones.
- 16. Twig.
- 17. Twig enlarged.

FIGURES 18, 19. *Widdringtonites reichii* (Ettingshausen) Heer. Cone-bearing twigs from the Cenomanian of Dalmatia, introduced for comparison.

All the specimens except those shown in figures 18 and 19 are from the Middendorf arkose member of the Black Creek formation.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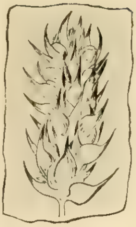
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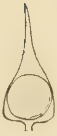
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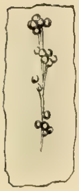
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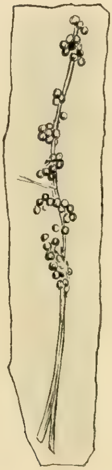
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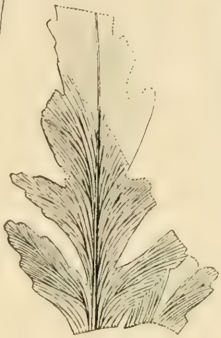
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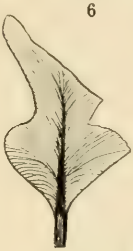
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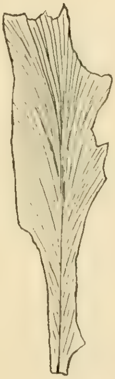
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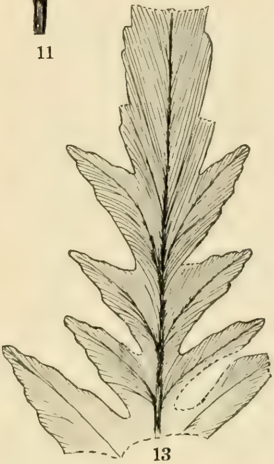
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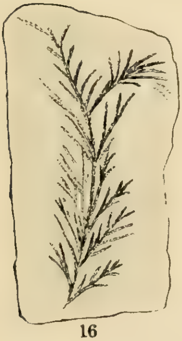
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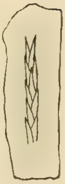
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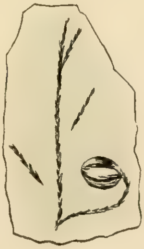
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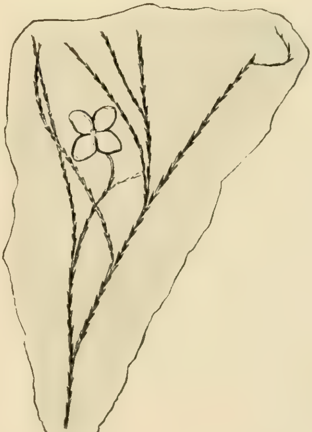

19

UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE III.

PLATE III.

	Page.
FIGURE 1. *Araucaria darlingtonensis* Berry, near Darlington	20
FIGURE 2. *Brachyphyllum macrocarpum* Newberry, Middendorf	21
FIGURE 3. *Heterolepis cretaceus* Berry, Rocky Point	27
FIGURE 4. *Cephalotaxospermum carolinianum* Berry, near Florence	18
FIGURE 5. *Strobilites anceps* Berry, near Darlington	27
FIGURES 6, 7. Detached leaves of *Araucaria bladenensis* Berry, near Florence	19

The specimens shown in figures 2 and 3 are from the Middendorf arkose member of the Black Creek formation. Those shown in figures 1, 4, 5, 6, and 7 are from other beds in the Black Creek formation.

1

2

3

4

5

6

7

UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE IV.

PLATE IV.

Page.

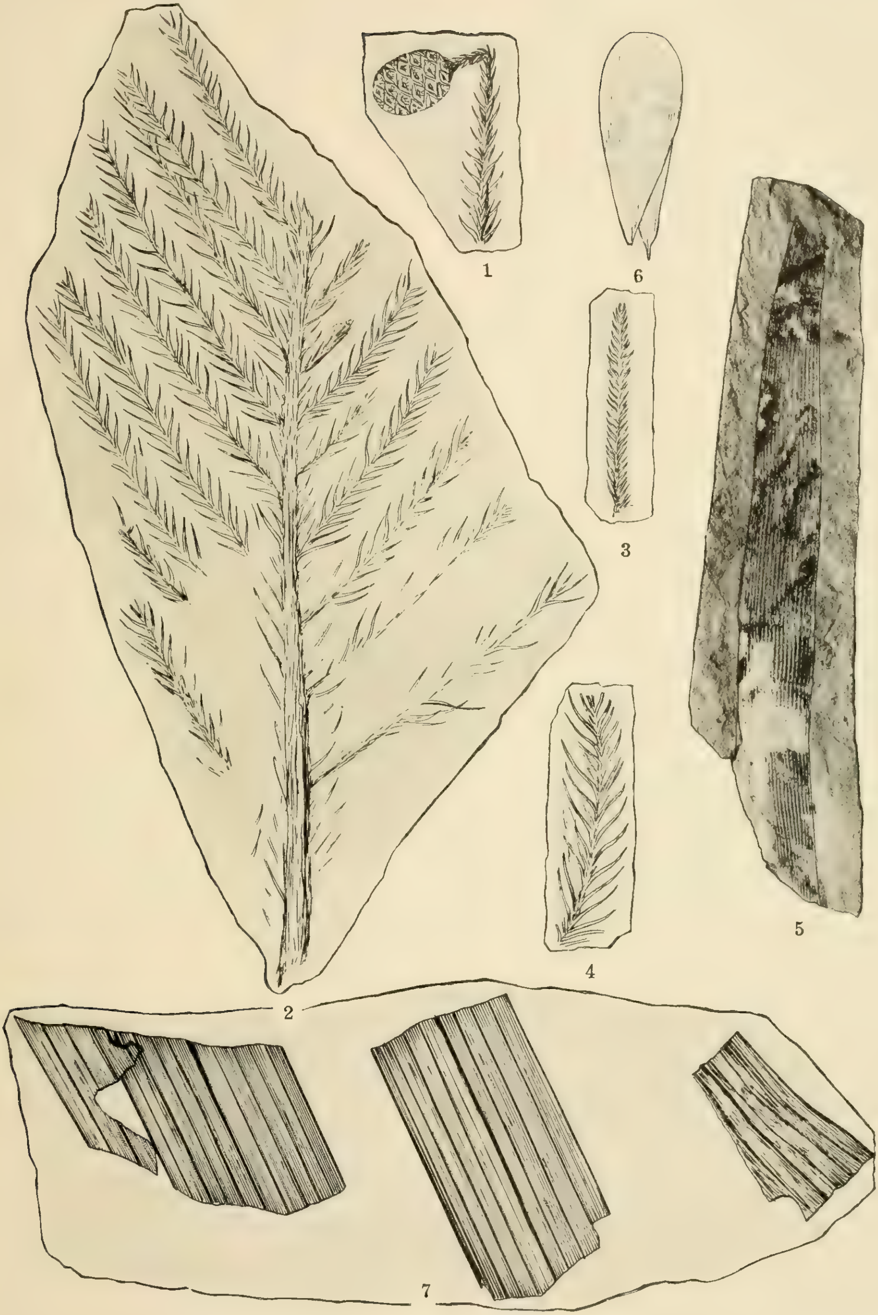
FIGURES 1–4. *Sequoia reichenbachi* (Geinitz) Heer, Middendorf 23
  1. Cone-bearing twigs.
  2–4. Twigs showing variations in size and appearance.

FIGURE 5. *Podozamites knowltoni* Berry, Rocky Point 16

FIGURE 6. *Potamogeton middendorfensis* Berry, Middendorf 27

FIGURE 7. *Arundo grœnlandica* Heer (?), Rocky Point 28

All the specimens are from the Middendorf arkose member of the Black Creek formation.



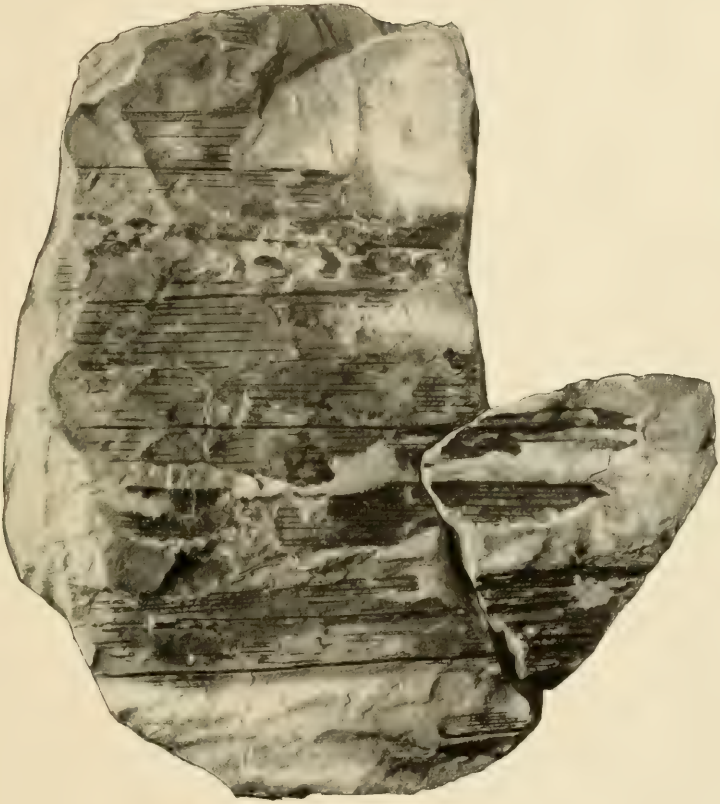
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE V.

PLATE V.

Page.

Sabalites carolinensis Berry, showing broad rays. From Middendorf arkose member of the Black Creek formation, near Langley -- 29

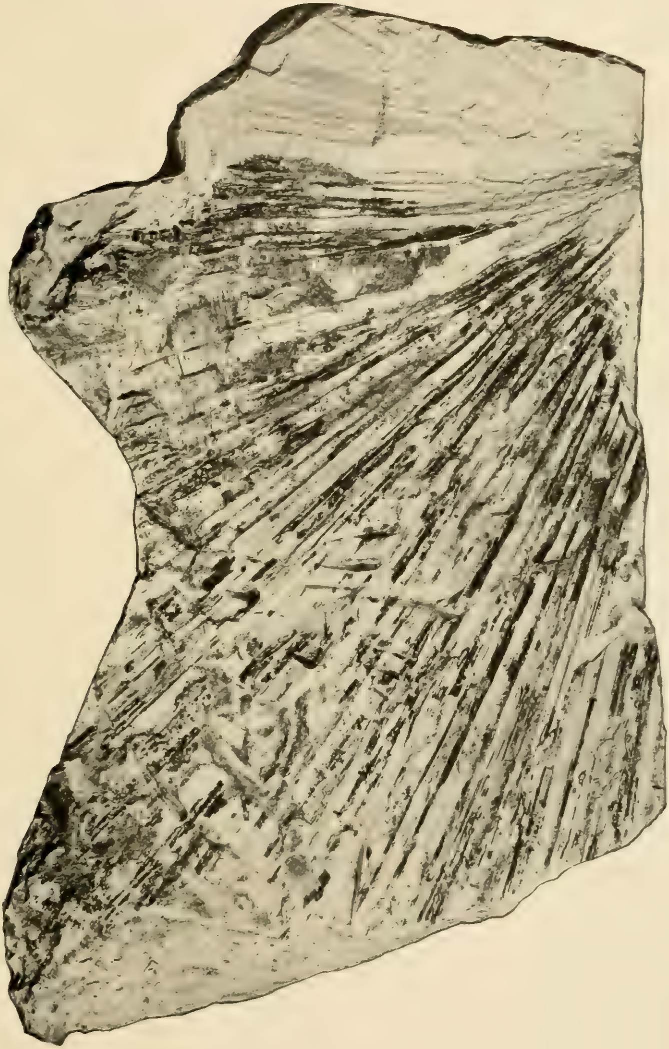


UPPER CRETACEOUS PLANT FROM SOUTH CAROLINA.

PLATE VI.

PLATE VI.

	Page.
Sabalites carolinensis Berry, showing keeled and narrowed rays near point of insertion on the rachis. From Middendorf arkose member of the Black Creek formation; near Langley	29



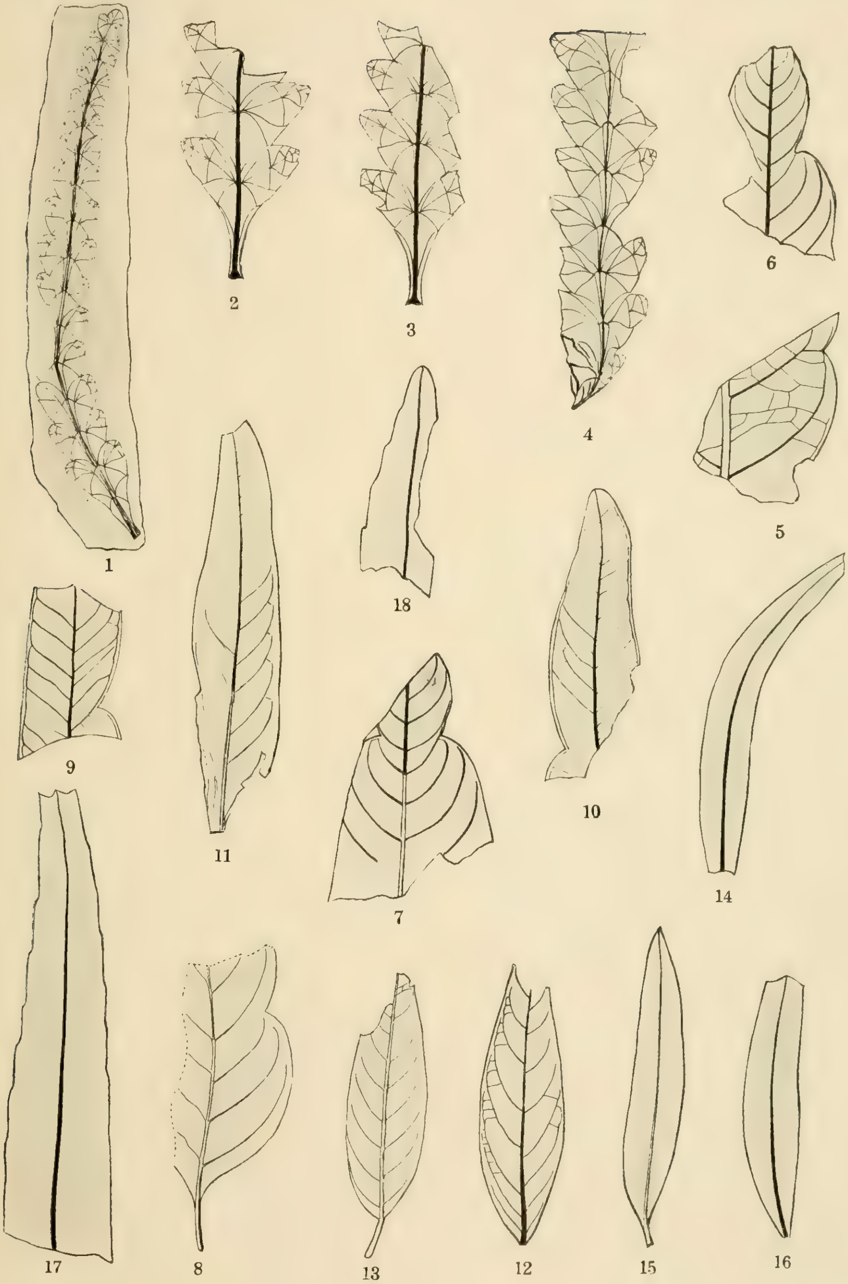
UPPER CRETACEOUS PLANT FROM SOUTH CAROLINA.

PLATE VII.

PLATE VII.

	Page.
FIGURES 1–4. *Moriconia americana* Berry, Middendorf	26
FIGURES 5–10. *Crotonophyllum panduræformis* Berry	48
5. Rocky Point.	
6–8. Langley.	
9–10. Middendorf.	
FIGURES 11–13. *Salix lesquereuxii* Berry	33
11. Middendorf.	
12. Rocky Point.	
13. Langley.	
FIGURES 14–16. *Salix flexuosa* Newberry, Middendorf	32
FIGURES 17, 18. *Myrica brittoniana* Berry, Black Creek	31

All the specimens except those shown in figures 17 and 18 are from the Middendorf arkose member of the Black Creek formation. The specimens shown in figures 17 and 18 are from other beds in the Black Creek formation.



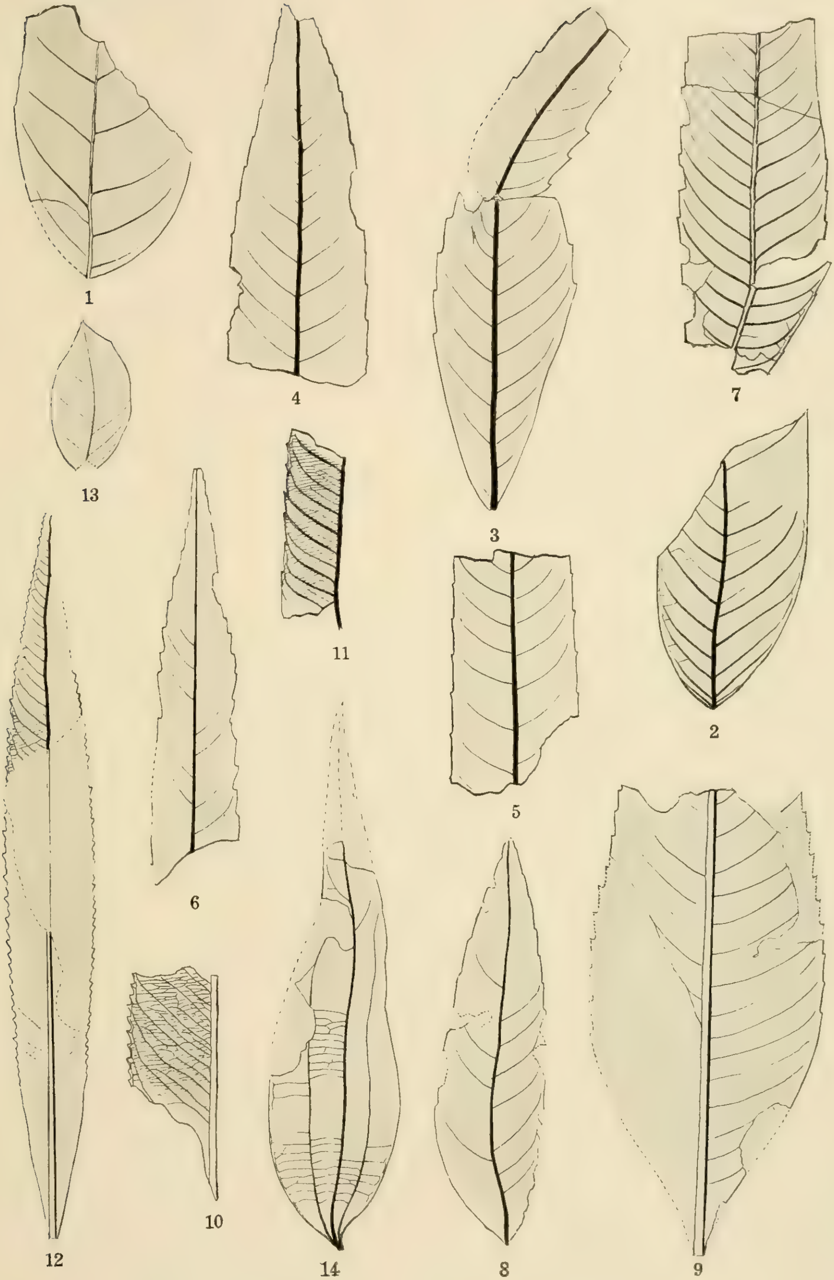
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE VIII.

PLATE VIII.

	Page.
FIGURES 1, 2. *Juglans arctica* Heer, Rocky Point	30
FIGURES 3–9. *Dewalquea smithi* Berry, near Langley	41
FIGURES 10–12. *Salix sloani* Berry, near Langley	34
FIGURE 13. *Leguminosites middendorfensis* Berry, Middendorf	46
FIGURE 14. *Cinnamomum middendorfensis* Berry, Middendorf	55

All the specimens are from the Middendorf arkose member of the Black Creek formation.



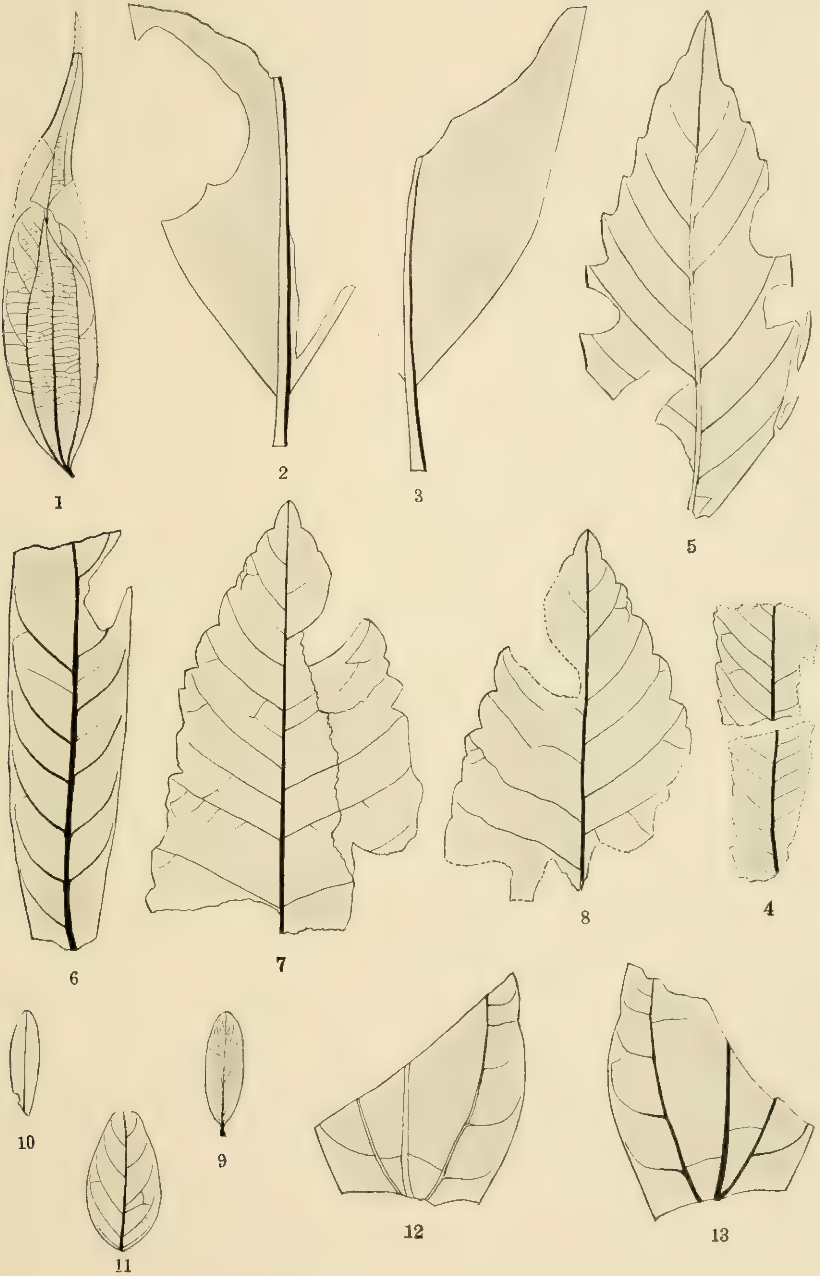
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE IX.

PLATE IX.

	Page.
FIGURE 1. *Cinnamomum middendorfensis* Berry, Middendorf	55
FIGURES 2, 3. *Magnolia tenuifolia* Lesquereux (?), Middendorf	44
FIGURE 4. *Myrica elegans* Berry, near Darlington	31
FIGURE 5. *Quercus pseudowestfalica* Berry, Rocky Point	35
FIGURE 6. *Sapindus morrisoni* Heer, near Langley	49
FIGURES 7, 8. *Rhus darlingtonensis* Berry, near Darlington	51
FIGURES 9, 10. *Acaciaphyllites grevilleoides* Berry, Middendorf	45
FIGURE 11. *Leguminosites robiniifolia* Berry, Langley	46
FIGURES 12, 13. *Cinnamomum newberryi* Berry, Rocky Point	54

All the specimens except those shown in figures 4, 7, and 8 are from the Middendorf arkose member of the Black Creek formation. The specimens shown in figures 4, 7, and 8 are from other beds of the Black Creek formation.



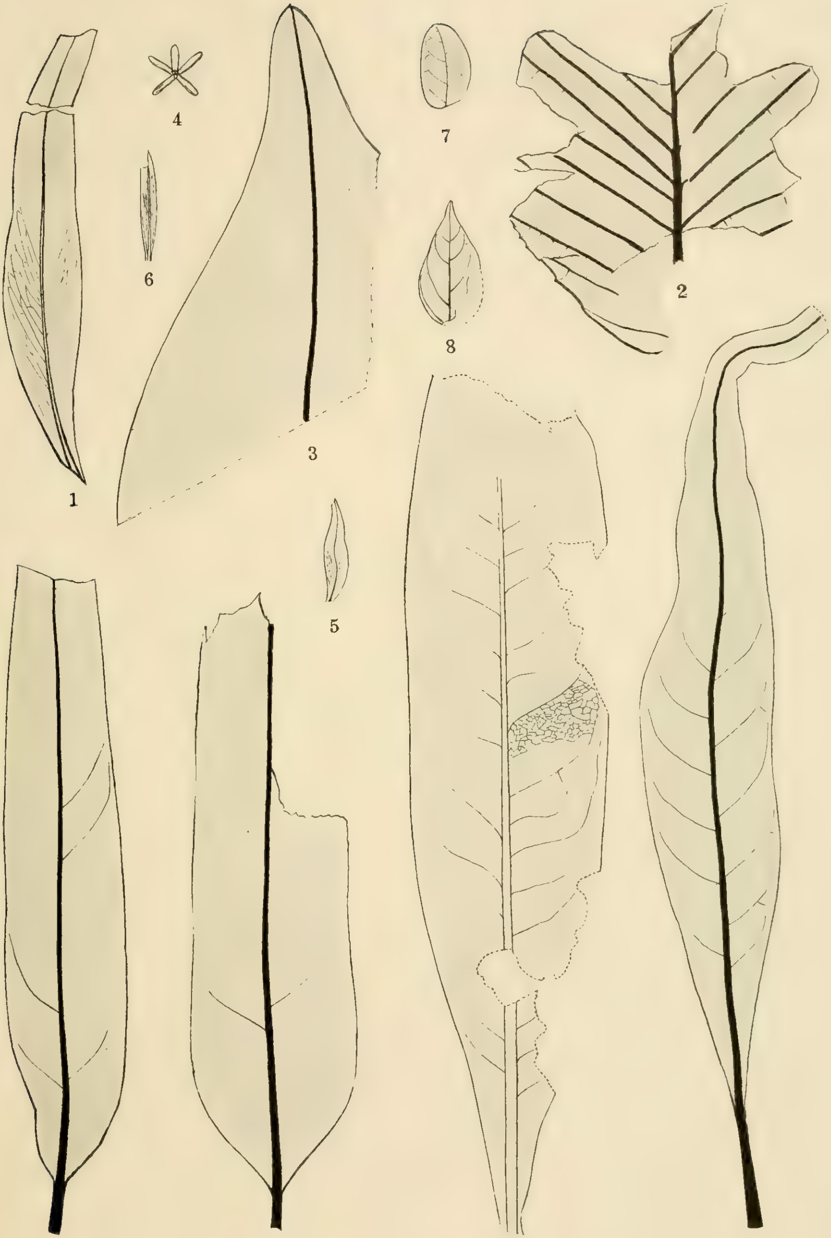
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE X.

PLATE X.

	Page.
FIGURE 1. *Proteoides lancifolius* Heer, Middendorf	40
FIGURE 2. *Hamamelites? cordatus* Lesquereux, Rocky Point	45
FIGURE 3. *Magnolia capellinii* Heer (?), Rocky Point	43
FIGURE 4. *Calycites middendorfensis* Berry, Middendorf	63
FIGURE 5. *Proteoides parvula* Berry, Middendorf	40
FIGURE 6. *Pachystima? cretacea* Berry, Middendorf	49
FIGURE 7. *Cæsalpinia middendorfensis* Berry, Middendorf	46
FIGURE 8. *Salix pseudohayei* Berry, Middendorf	34
FIGURES 9, 10. *Quercus sumterensis* Berry, Rocky Point	35
FIGURE 11. *Ficus atavina* Heer, Rocky Point	36
FIGURE 12. *Ficus crassipes* Heer, Rocky Point	37

All the specimens are from the Middendorf arkose member of the Black Creek formation.



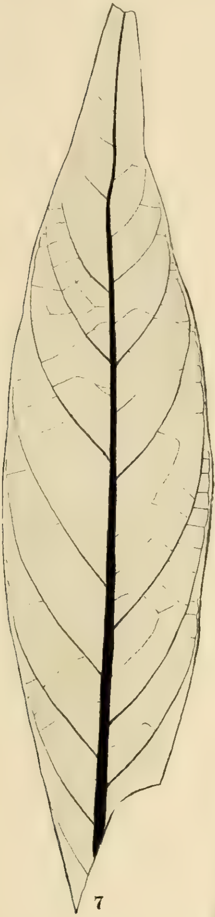
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE XI.

PLATE XI.

	Page.
FIGURE 1. *Salix flexuosa* Newberry, Langley	32
FIGURE 2. *Laurus plutonia* Heer, Langley	52
FIGURE 3. *Diospyros primæva* Heer, Langley	61
FIGURES 4–7. *Ficus krausiana* Heer, Rocky Point	38

All the specimens are from the Middendorf arkose member of the Black Creek formation.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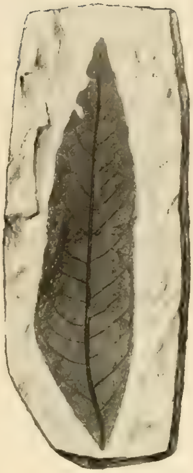
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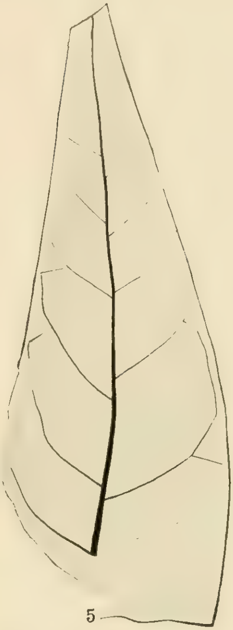
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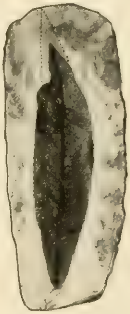
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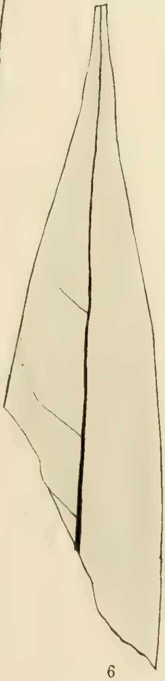
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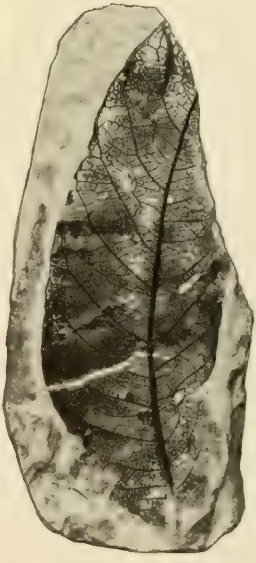
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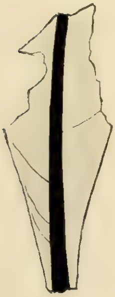
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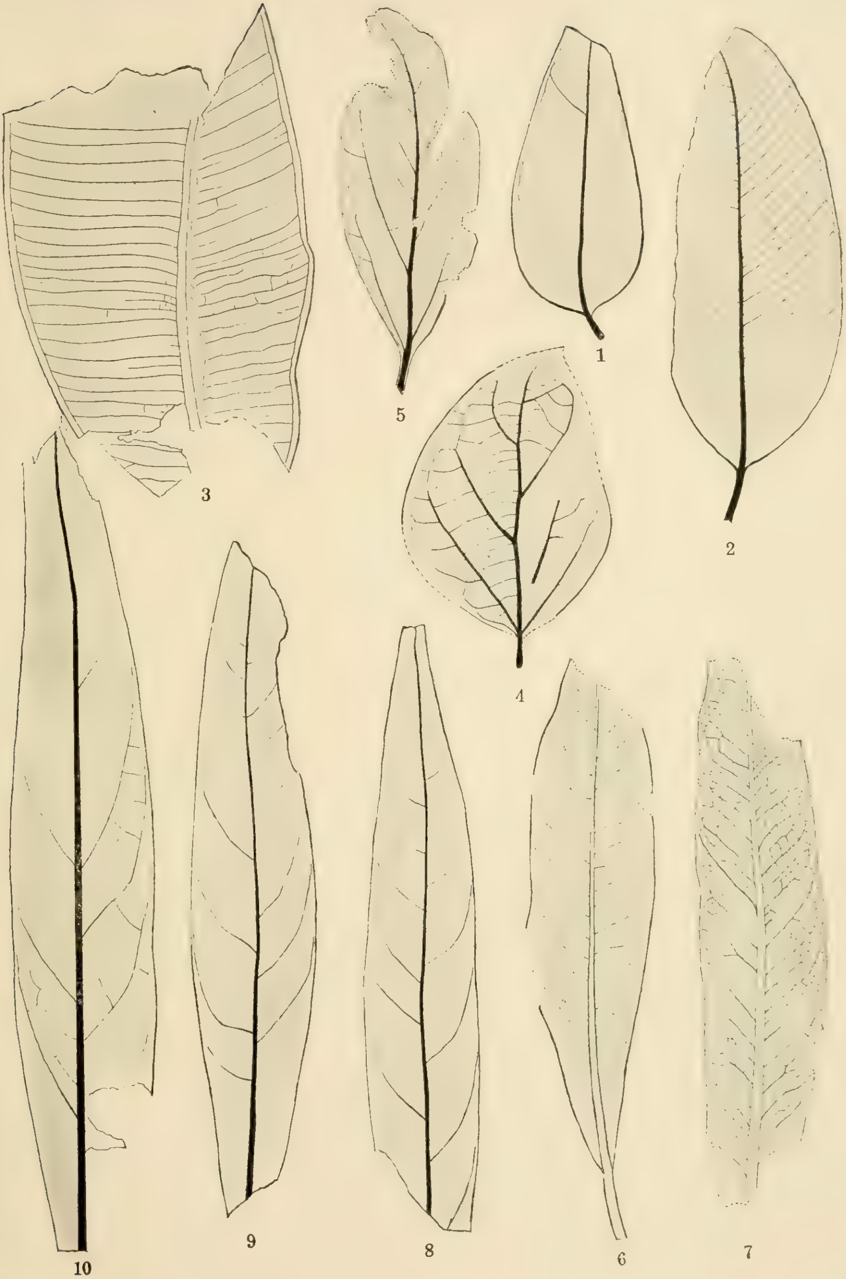
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE XII.

PLATE XII.

	Page.
FIGURES 1–3. *Ficus stephensoni* Berry	38
1, 3. Langley.	
2. Middendorf.	
FIGURE 4. *Ficus celtifolius* Berry, Middendorf	37
FIGURE 5. *Momisia carolinensis* Berry, Middendorf	36
FIGURE 6. *Laurophyllum elegans* Hollick, Middendorf	53
FIGURE 7. *Laurophyllum nervillosum* Hollick, Middendorf	54
FIGURES 8–10. *Ficus crassipes* Heer, Rocky Point	37

All the specimens are from the Middendorf arkose member of the Black Creek formation.



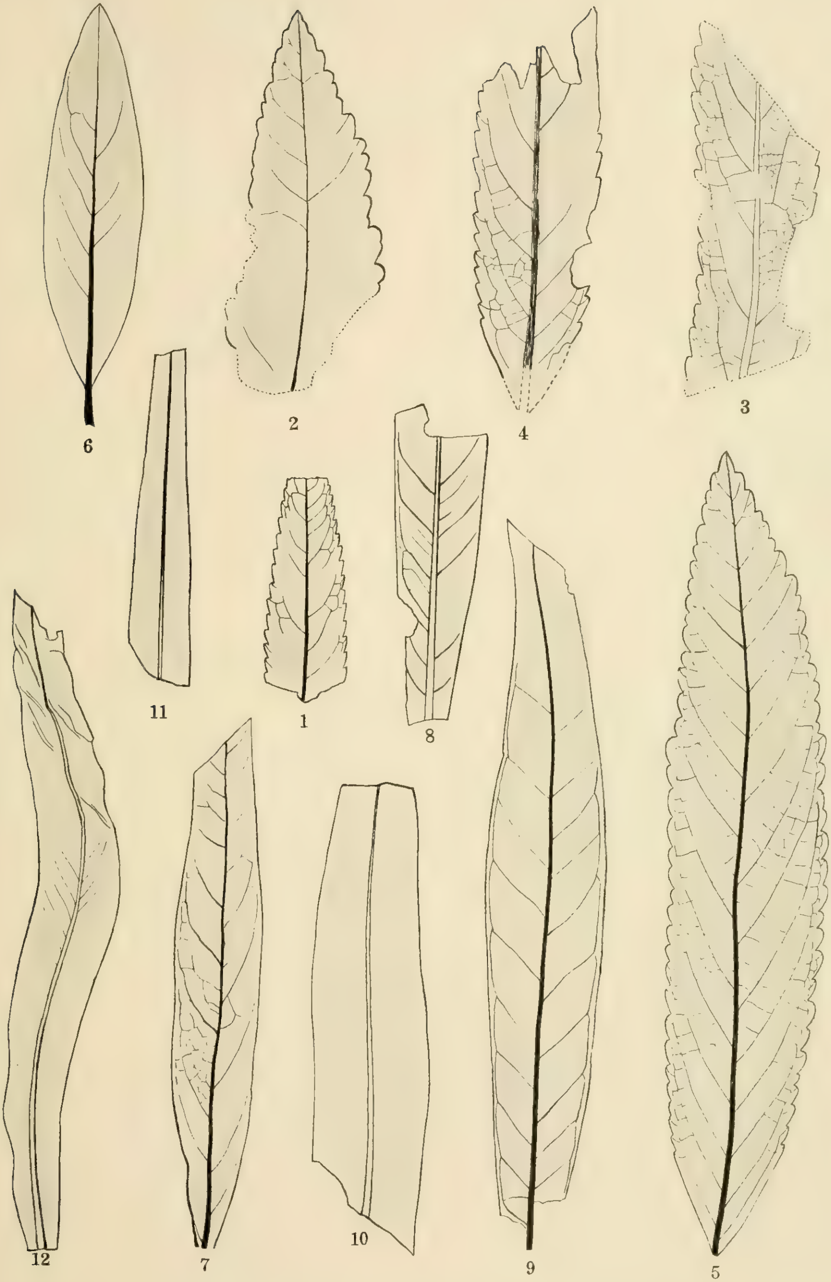
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE XIII.

PLATE XIII.

	Page.
Figures 1–5. *Celastrophyllum carolinensis* Berry	51
1–4. Middendorf.	
5. Restoration.	
Figure 6. *Laurus plutonia* Heer, Middendorf	52
Figure 7. *Laurus atanensis* Berry, Rocky Point	53
Figures 8–12. *Eucalyptus geinitzi* (Heer) Heer	56
8, 10, 11, 12. Middendorf.	
9. Rocky Point.	

All the specimens are from the Middendorf arkose member of the Black Creek formation.



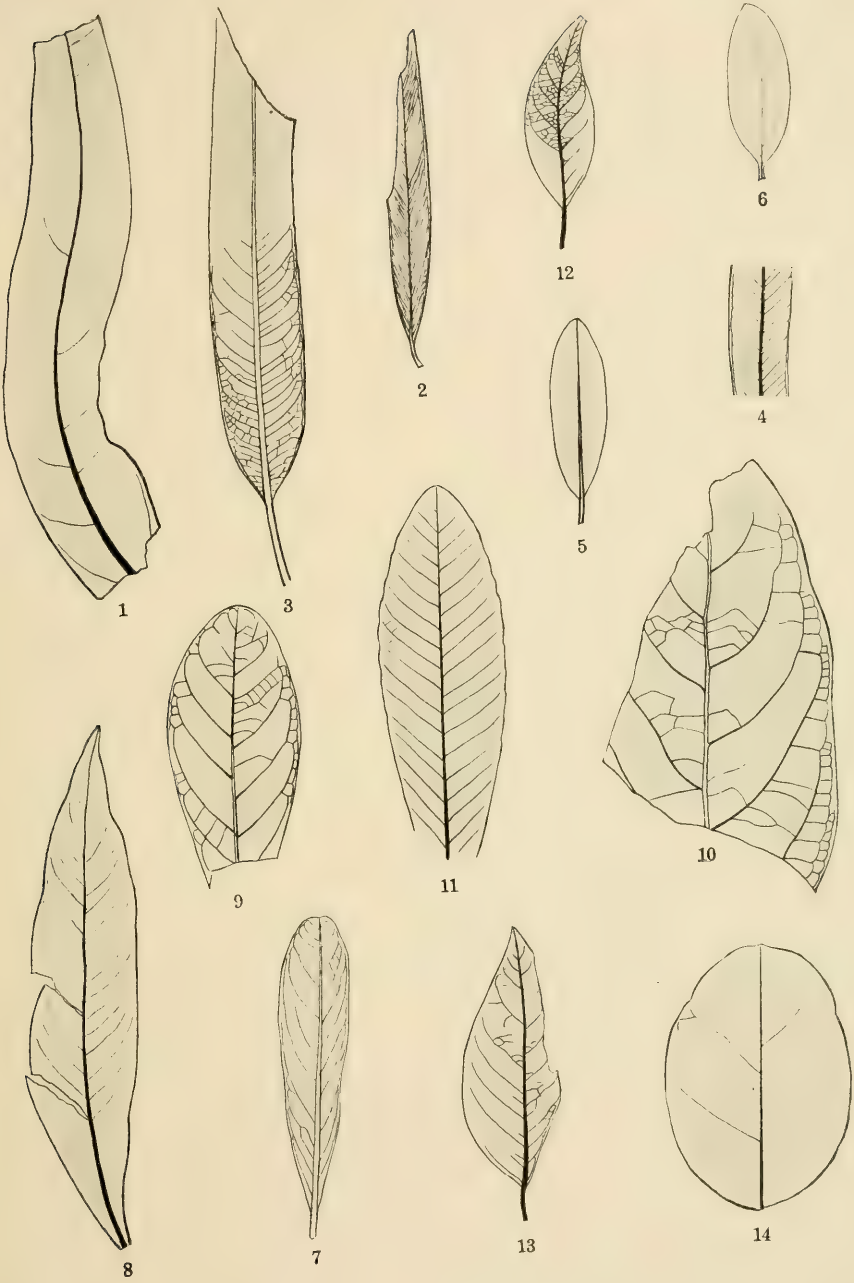
UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

PLATE XIV.

PLATE XIV.

	Page.
Figure 1. *Eucalyptus geinitzi* (Heer) Heer, Rocky Point	56
Figure 2. *Eucalyptus angusta* Velenovsky, Black Creek	55
Figures 3, 4. *Eucalyptus wardiana* Berry (?), Middendorf	57
Figures 5, 6. *Andromeda novæcæsareæ* Hollick, Middendorf	58
Figure 7. *Andromeda euphorbiophylloides* Berry, Middendorf	59
Figure 8. *Illicium watereensis* Berry, Rocky Point	44
Figure 9. *Myrsine gaudini* (Lesquereux) Berry, Langley	61
Figure 10. *Andromeda grandifolia* Berry, Rocky Point	59
Figure 11. *Celastrophyllum elegans* Berry, Rocky Point	50
Figures 12, 13. *Diospyros primæva* Heer, Langley	61
Figure 14. *Diospyros rotundifolia* Lesquereux, Rocky Point	62

All the specimens except that shown in figure 2 are from the Middendorf arkose member of the Black Creek formation. The specimen shown in figure 2 is from another part of the Black Creek formation.



UPPER CRETACEOUS PLANTS FROM SOUTH CAROLINA.

THE UPPER CRETACEOUS FLORA OF GEORGIA.

INTRODUCTION.

Up to the time of the present study no fossil plants had been specifically recorded from the Coastal Plain of Georgia, although S. W. McCallie mentions several Eocene plant localities and one of Cretaceous age in his report on the underground waters of Georgia,[1] and one of the localities which has furnished materials for the following notes is mentioned by Otto Veatch in his recent report on the clay deposits of Georgia.[2] In 1894 D. W. Langdon recorded leaf fragments in the Cretaceous at Chimney Bluff on Chattahoochee River,[3] and in a recent note on this flora the writer [4] lists a number of the forms found in the Georgia Cretaceous and discusses briefly the botanic and ecologic conditions which they indicate.

Both Lower and Upper Cretaceous rocks are present in Georgia. The Lower Cretaceous sands and clays form a belt of varying width extending across the State along the eastern border of the Piedmont Plateau from Augusta to Columbus and appear to be continuous with the so-called "Hamburg beds" of South Carolina. They are probably to be correlated with the Patuxent ("Cape Fear") formation of North Carolina, which in turn is correlated with the Patuxent formation of Maryland and Virginia, rather than with the younger Tuscaloosa formation of western Alabama, as has been done by Veatch,[2] for L. W. Stephenson has shown that the Tuscaloosa overlies them unconformably in the area of their most western outcrop, a short distance west of Montgomery, Ala.

The Upper Cretaceous formations of Georgia have been recently studied by Mr. Stephenson, who has in preparation a detailed report on the geology, and they will not be considered in detail in the present contribution. A brief statement is, however, necessary, and the writer is under obligations to Mr. Stephenson for furnishing data, especially regarding the plant localities near Buena Vista and Byron. These localities have not been visited by the writer, who is familiar only with the Cretaceous of the Chattahoochee River section and of an area near Columbus, Ga.

GEOLOGY OF THE UPPER CRETACEOUS DEPOSITS OF GEORGIA.

Deposits of Upper Cretaceous age in Georgia are confined to a triangular area lying west of Ocmulgee River and are transgressed east of that point by the Eocene. The relatively narrow base of this triangle is formed by Chattahoochee River, and the apex points somewhat north of east. These Upper Cretaceous deposits represent the Eutaw and Ripley formations, and each formation is subdivided on more or less well-marked lithologic grounds into the following divisions:

- Ripley formation.
    - Providence sand member.
    - Middle division ("Renfroes marl" of Veatch).
    - Cusseta sand member.
- Eutaw formation.
    - Tombigbee sand member.
    - Lower division.

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[1] Bull. Georgia Geol. Survey No. 15, 1908, pp. 36, 336, 347.

[2] Bull. Georgia Geol. Survey No. 18, 1909, p. 88.

[3] Langdon, D. W., Report on the geology of the Coastal Plain of Alabama, 1894, p. 440.

[4] Berry, E. W., Bull. Torrey Bot. Club, vol. 37, 1910, pp. 503–511, figs. 1, 2.

RIPLEY FORMATION.

Cusseta sand member.—The Cusseta member is typically developed in southeastern Chattahoochee County, near the town of Cusseta, where it consists of noncalcareous, rather micaceous, mostly unconsolidated quartz sands with local lenses of laminated clays and more extensive lenses of dark, massively bedded clays. It loses its distinctive character to the west along Chattahoochee River, where it is more or less glauconitic and fossiliferous, and to the northeast, where it merges with the underlying and overlying Upper Cretaceous sands. Beds believed to represent this horizon are fossiliferous along the Chattahoochee and contain plant fossils near Buena Vista and near Byron.

Middle division.—The middle part of the Ripley formation consists essentially of massive, micaceous, calcareous, and in many places glauconitic sand with calcareous nodules and dark, argillaceous, pyritiferous, lignitic sands and clays, the sands predominating. These deposits preserve their identity more or less completely from Chattahoochee River eastward across Stewart, Marion, and Schley counties, merging in Macon County with the underlying and overlying Cretaceous sands. They carry an abundant marine fauna, and beds of this age across the border in Alabama have yielded a small flora markedly different in character from that described in the following pages.

Providence sand member.—The Providence sand consists essentially of variegated, more or less cross-bedded sands which pass gradually into the underlying middle division of the Ripley ("Renfroes marl" of Veatch), with the representatives of which they merge toward the east. They are unfossiliferous and hence without interest in the present connection.

EUTAW FORMATION.

Lower division.—The part of the Eutaw formation in the Georgia area which underlies the Tombigbee member consists predominantly of sands, coarse toward the landward margin, and elsewhere in many places calcareous and locally argillaceous and more or less glauconitic. Lenses of dark laminated clay are not uncommon and contain many large teredo-bored logs. Silicified wood is common in the sands. At certain localities molluscan remains are not uncommon, and the clay lenses ordinarily carry vegetable matter. Along Chattahoochee River the sands of the lower division of the Eutaw are in places semilithified by the development of several courses of nodules cemented by carbonate of lime. Eastward the deposits pass into unconsolidated, cross-bedded, ferruginous, and unfossiliferous sands.

The areal extent of these lower deposits is not great. They underlie the northern part of Chattahoochee and Marion counties, a small part of southern Muscogee County, and western Taylor County, beyond which they are not separable from the similar unconsolidated sands which characterize the overlying Upper Cretaceous deposits. They contain a fairly representative flora both in their basal and upper portions.

Tombigbee sand member.—The Georgia representative of the Tombigbee sand member of the Eutaw formation of Mississippi and Alabama is distinctive in character only along Chattahoochee River and for a few miles to the northeast, where it consists of more or less calcareous clays which are locally lignitic and of more or less argillaceous sands with thin layers of calcareous nodules. Eastward it can not be traced beyond Marion County, where it becomes more sandy and is indistinguishable from the adjacent deposits of the Eutaw formation and from the overlying Cusseta sand member of the Ripley formation. It contains marine invertebrates but has failed to yield any recognizable plant remains.

PLANT LOCALITIES.

Determinable fossil plants have been collected in the Upper Cretaceous of Georgia from five different localities, each of which will be briefly described.

McBRIDES FORD.

The locality at McBrides Ford is on the left bank of Upatoi Creek in Chattahoochee County, about 10 miles southeast of Columbus, Ga.

The lower Eutaw deposits, which are above the ford, rest with a marked unconformity on Lower Cretaceous clays. At the base they show fine gravel, grading upward into coarse cross-bedded sands with clay laminæ. At one point about 10 feet above low water a small lens of dark-drab clay, not more than 12 or 15 inches in thickness and pinching out laterally within a few feet, furnished the plant remains listed from this locality. Two large leaves of Manihotites were lying close together and possibly were derived from the same plant. Similar small lenses of clay along the low bank of the creek showed traces of leaves and much comminuted vegetable matter but nothing recognizable.

The species identified from this locality only a few feet above the base of the formation and near its landward margin are:

Andromeda cretacea Lesquereux?
Andromeda wardiana Lesquereux.
Androvettia elegans Berry.
Aralia eutawensis Berry.
Brachyphyllum macrocarpum formosum Berry.
Cinnamomum heerii Lesquereux?
Cinnamomum newberryi Berry.
Eucalyptus angusta Velenovsky.
Ficus ovatifolia Berry.
Juglans arctica Heer?
Magnolia boulayana Lesquereux.
Magnolia capellinii Heer.
Manihotites georgiana Berry.
Menispermites variabilis Berry.
Paliurus upatoiensis Berry.
Salix flexuosa Newberry.
Sequoia reichenbachi (Geinitz) Heer.
Tumion carolinianum Berry?
Zizyphus laurifolius Berry.

The Sequoia and Androvettia are the most abundant forms. In addition to the plants in the list several species of dicotyledons represented by unidentifiable fragments and a specimen of an undeterminable fern of the Asplenium type were collected.

BROKEN ARROW BEND.

The locality at Broken Arrow Bend includes outcrops on both banks of Chattahoochee River about 13 miles below Columbus. The one farthest up the river, on the Alabama bank, contains marine invertebrates; the other, on the left bank, about 100 yards farther downstream, in Chattahoochee County, Ga., shows a much more extensive section and includes the fossil plants enumerated below. At the base of the bluff in places the much-eroded surface of the Lower Cretaceous rises to a height of about 5 feet. Overlying this are coarse cross-bedded sands of the lower Eutaw with gravel, much lignite, and a few small lenses of dark "shaly" clay about a foot in thickness and 10 to 15 feet in diameter, carrying poor leaf impressions and considerable comminuted vegetable matter.

The identifiable species are:

Malapoenna horrellensis Berry?
Phragmites pratti Berry.
Salix eutawensis Berry.
Salix flexuosa Newberry.
Sequoia reichenbachi (Geinitz) Heer.

An undeterminable leaf of Ficus was also found here. The Sequoia is characteristic and is the most abundant type. Next in abundance is *Salix eutawensis*, the leaves of which are, however, usually much broken.

CHIMNEY BLUFF.

The locality at Chimney Bluff is on the left bank of Chattahoochee River about 22 miles below Columbus, in Chattahoochee County. (See Pl. XV, *A*.)

At this point the Eutaw shows about 25 feet of irregularly bedded, laminated and cross-bedded, very lignitic, pyritiferous sand and clay, with small lenses of dark-drab clay carrying plant remains, the whole overlain by a lens of fine gray sand about 10 to 15 feet thick, above which, without unconformity, are about 50 feet of yellowish or greenish very argillaceous sands which carry casts of marine invertebrates and which are believed to represent the Tombigbee sand.

The identifiable plants, which are from a layer near the top of the lower division of the Eutaw, are as follows:

Araucaria bladenensis Berry.
Araucaria jeffreyi Berry.
Ficus crassipes Heer.
Ficus krausiana Heer.
Salix flexuosa Newberry.
Salix lesquereuxii Berry.
Sequoia reichenbachi (Geinitz) Heer.

At this locality the Sequoia is rare and the commonest plant is *Araucaria bladenensis*, represented for the most part by macerated twigs and detached leaves, though better preserved twigs of considerable size are not uncommon. The lower part of the exposure is remarkable for its lignite. Large teredo-bored logs, some of them 2 to 3 feet in diameter, are not uncommon, and pellets of fossil resin (amber) are also present. In view of the persistent association of this fossil resin with Araucaria remains from North Carolina southward it seems probable that not all Upper Cretaceous ambers are derived from species of Pinus, though this, as shown by Hollick and Jeffrey, is the source of the amber from Staten Island, N. Y.

Leaf impressions were discovered at this locality in 1888 by the late D. W. Langdon, of the Alabama Geological Survey, who mentioned their occurrence in several publications, but no collections were made until the writer's visit in 1909.

LOCALITY NEAR BUENA VISTA.

The fossil plants from the locality near Buena Vista (see Pl. XV, *B*) were collected by L. W. Stephenson in a gully along the Buena Vista-Tazewell road about 6 miles northeast of Buena Vista, in Marion County, in deposits referred by him to the Cusseta sand member of the Ripley formation. The species identified are the following:

Andromeda novaecæsareæ Hollick.
Araucaria bladenensis Berry.
Doryanthites cretacea Berry.
Eucalyptus angusta Velenovsky.
Ficus georgiana Berry.
Manihotites georgiana Berry.

The leaf impressions are scattered and poor, perhaps the most abundant form being the Doryanthites. The Araucaria is represented by detached leaves, and all of the remains show evidence of trituration.

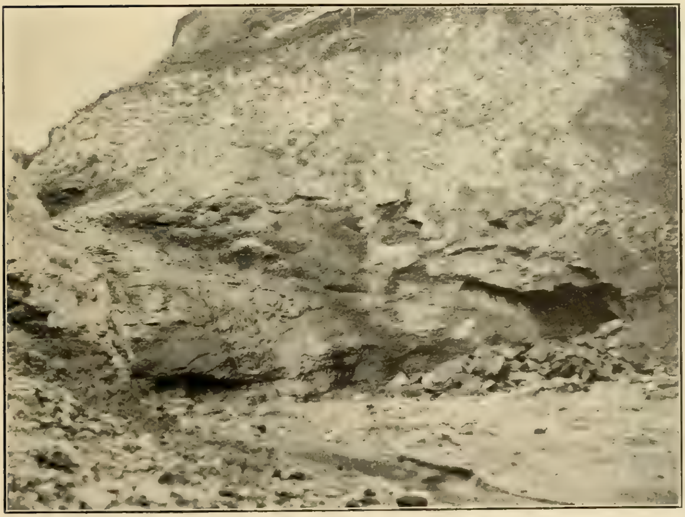
LOCALITY NEAR BYRON.

The locality about 1½ miles northeast of Byron, in Houston County, is in a cut of the Central of Georgia Railway on the north side of the track The plants were collected by L. W. Stephenson and are referred by him to the Cusseta sand member. The materials in this area are predominantly coarse, cross-bedded, rather incoherent arkosic sands with local clay lenses of small extent. The leaf remains from this point are contained in a massive dark-drab clay which carries much comminuted vegetable matter and grades both horizontally and vertically into laminated clay with fine sand partings. The plants are few and poor and include the following recognizable forms:

Araucaria jeffreyi Berry.
Cunninghamites elegans (Corda) Endlicher.
Dryopterites stephensoni Berry.

The Cunninghamites is the commonest form but is very poorly preserved. The collection also contains undeterminable fragments of dicotyledonous leaves.

A. PLANT LOCALITY AT CHIMNEY BLUFF, CHATTAHOOCHEE RIVER, GA.



B. PLANT LOCALITY IN THE CUSSETA SAND MEMBER OF THE RIPLEY FORMATION NEAR BUENA VISTA, GA.

SYSTEMATIC DESCRIPTION OF THE FLORA.

Phylum PTERIDOPHYTA.

Order FILICALES.

Family POLYPODIACEÆ.

Genus DRYOPTERITES Berry.

DRYOPTERITES STEPHENSONI sp. nov.

Plate XVII, figures 1 and 2.

Description.—Fronds bipinnate or possibly tripinnate. Pinnules thick in texture, ovate to lanceolate in outline, ascending, merging toward the apex of the pinnæ. A single vein enters each pinnule, branching from the rachis at an extremely acute angle and immediately breaking up into three branches, the upper as a rule remaining simple and running to the upper margin, the lower generally forking once and running to the lower lateral margin, and the middle dividing four or five times to form the main vascular system of the pinnule. The distal branches commonly remain simple and the proximal generally fork once.

This species is based upon the specimen figured and its counterpart. It is quite distinct from any ferns previously known from the American Upper Cretaceous but suggests various forms previously described, for example, the fern remains described by Debey and Ettingshausen from Aachen (Emscherian), on the Prussian border, as *Pteridoleimma gymnorachis*.[1] Other forms which show a superficial resemblance to the one under consideration are those described by Kerner from Lesina, Dalmatia (Cenomanian), as various species of Pachypteris.[2]

Still other fern remains described as *Sphenopteris grevillioides* Heer,[3] *Grevillea tenera* Velenovsky,[4] and *Thyrsopteris grevillioides* Hollick,[5] which range from the Kome beds (Barremian) of Greenland to the Upper Cretaceous of Marthas Vineyard (Magothy formation), are suggestive of the Georgia fern in general aspect but are seen to differ both in outline and venation when careful comparisons are instituted. The modern genus Dryopteris of Adanson (Aspidium Swartz) has more than 1,000 species of wide geographic distribution in the existing flora. Fossil species have been described from the Lower Cretaceous upward.[6] The Upper Cretaceous records include *Dryopteris oerstedi* (Heer) Knowlton from the Atane and Patoot beds of Greenland[7] and *Dryopteris kennerleyi* (Newberry) Knowlton from Vancouver Island, neither of which appears to be closely related to the Georgia plant.

Occurrence.—Cusseta sand member of the Ripley formation, cut on Central of Georgia Railway, 1½ miles northeast of Byron, Houston County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Phylum SPERMOPHYTA.

Class GYMNOSPERMÆ.

Order CONIFERALES.

Genus ANDROVETTIA Hollick and Jeffrey.

ANDROVETTIA ELEGANS sp. nov.

Plate XVIII, figures 1–10.

Description.—These remains consist of bifacial leafy twigs arranged in a distichous and apparently opposite manner on naked stems, very fernlike in general aspect. These phylloclad-like lateral twigs are not simple shoots but reduced branches of a higher order, for they are made up of regularly alternating leaves and reduced leaf-bearing lateral twigs in the axils of these leaves. Phyllotaxy and arrangement of twigs are apparently cyclic throughout, but much masked by reduction, especially of those leaves on the flat surfaces. The lateral leaves are opposite, stout, falcate, pointed, and markedly decurrent, with a single immersed stout leaf trace; proximally they coalesce with their fellows. The leaves on the upper and lower surfaces are apparent on magnification as bluntly rounded scales along the middle of the phylloclad. Between each successive lateral leaf there is a rounded toothed lobe about twice as long as the leaves which represent a vestigial axillary branch. These lobes show vestiges of several leaves, not only by the marginal teeth but also by the lines of adhesion, which can be traced for greater or less distances inward. The vascular system of these reduced lateral twigs can not be made out satisfactorily. Each shows a single once-forked strand, the two forks running to the tips of the reduced basal leaves of the twig. Whether this represents all that is left of the vascular system of these twigs can not be made out. In the more reduced *Androvettia carolinensis* Berry these twigs are usually represented by a single rounded lobe which contains but one once-forked strand like that in the Georgia material.

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[1] Denkschr. K. Akad. Wiss. Wien, vol. 17, 1859, p. 234, Pl. VII, figs. 21, 22.

[2] Jahrb. K.-k. geol. Reichsanstalt, vol. 45, 1895, pp. 39 et seq.

[3] Heer, Oswald, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 34, Pl. XI, figs. 10 and 11.

[4] Velenovsky, J., Die Flora der böhmischen Kreideformation, pt. 4, 1885, p. 11, Pl. VII, figs. 9, 14, and 16.

[5] Hollick, Arthur, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 31, Pl. I, figs. 10–13.

[6] These were set apart from the modern genus as the genus Dryopterites by the writer in 1911.

[7] The form identified as this species from the Patapsco formation of Virgina is *Cladophlebis browniana*.

Distally some specimens show clusters of small terete twigs in the axils of lateral leaves of the main shoots. These twigs are covered with small, ovate, appressed leaves. Similar objects are present in some of the material of *Androvettia statenensis* from Kreischerville, Staten Island, each of which springs from the axil of a normal leaf of the axillary shoot and is doubtfully interpreted as a male ament. This may be the nature of these remarkable objects, although no traces of pollen or pollen sacs can be made out in microscopic preparations of the Georgia fossil. They can hardly represent anything but aments or a most curious type of dimorphic foliage. The illustrations show typical specimens of the normal and dimorphic type, natural size and also enlarged 4 diameters, as well as the apical part of one of the lateral twigs of the normal type enlarged 45 diameters.

This remarkable genus was erected by Hollick and Jeffrey [1] for the reception of a single species discovered recently in the upper part of the Raritan formation near Kreischerville, Staten Island, and the describers content themselves with a very good account of this species and refrain from framing a generic diagnosis. This laudable conservatism is abundantly justified by the writer's discovery of two additional species which can not be generically separated from the Staten Island species and which furnish a number of additional characters that serve to isolate this genus.

These remains are all entirely fernlike in superficial appearance, uniformly coriaceous in texture, and by the details of their external characters and internal structure are indubitable gymnosperms of the order Coniferales. Their positive reference to the Araucarineæ by Hollick and Jeffrey will undoubtedly be questioned by many students.

Androvettia carolinensis is not common and is confined to a single locality on Tar River in North Carolina and to a recently discovered locality at about the same horizon near Iuka in northeastern Mississippi. It evidently had a wide range, and its scarcity in the fossil state may possibly be due to its habitat having been remote from the areas of sedimentation. What makes this theory seem plausible is the fact that although the remains are extremely coriaceous they are much broken both in North Carolina and Mississippi, as if they had been in the water a long time, and possibly they were brought down from the upland by streams. The Georgia material is more abundant, but is also confined to a single known locality. The lateral leaves along the edges of phylloclad-like twigs are markedly opposite and well developed and the scale leaves on its flat surfaces are less reduced than in *Androvettia statenensis* or *Androvettia carolinensis*. The lateral twigs are strictly opposite as in the course of the vascular bundles, which consist of a regular alternation of opposite simple bundles and dichotomously forked bundles. As the anatomy of these forms has not yet been studied the reader is referred to

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[1] Mem. New York Bot. Garden, vol. 3, 1909, p. 22.

Hollick and Jeffrey's memoir cited above, in which the histology of the Staten Island form is discussed.

Androvettia seems clearly distinct from Phyllocladus, and it is probably equally distinct from the various species of Protophyllocladus which have been recorded from the Raritan and later Cretaceous formations of North America. It seems equally distinct from Thinnfeldia but may prove to be related to Moriconia—in fact, the reduced lateral twigs are very suggestive of the similar twigs of *Moriconia americana* Berry, especially the forms of this species collected by the writer from clays in the Middendorf arkose member of the Black Creek formation of South Carolina. The comparison of Androvettia with the Lower Cretaceous species *Ctenopteria insignis, Zamiopsis insignis, Thinnfeldia marylandicum,* and *Plantaginopsis marylandica* by Hollick and Jeffrey is in the writer's opinion singularly unhappy. The last is a monocotyledon and the others either ferns or cycads, not even remotely related to the forms under discussion.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Genus **ARAUCARIA** Jussieu.

ARAUCARIA BLADENENSIS Berry.

Plate XIX, figures 1 and 2.

Araucaria bladenensis Berry, Bull. Torrey Bot. Club, vol. 35, 1908, p. 255, Pls. XII; XIII; and XIV, figs. 1-3.

This form is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (pp. 19-20).

This species, which is so exceedingly common in and characteristic of the Black Creek formation in the North Carolina area, and which is also found in the continuation of these beds in South Carolina, occurs in abundance in the lower part of the Eutaw of western Alabama. In Georgia it is represented at Buena Vista by detached but entirely characteristic leaves which are extremely rare. It is more common at Chimney Bluff, where both the detached leaves and the leafy twigs, often of considerable size, are abundant. The presence at the latter locality of a characteristic cone scale of *Araucaria jeffreyi* suggests the probability of the two being referable to the same species.

Occurrence.—Lower division of the Eutaw formation, Chimney Bluff, Chattahoochee County. (Collected by E. W. Berry.) Cusseta sand member of the Ripley formation, near Buena Vista, Marion County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

ARAUCARIA JEFFREYI Berry.

Araucaria jeffreyi Berry, Bull. Torrey Bot. Club, vol. 35, 1908, p. 258, Pl. XVI.

This species is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (pp. 20-21).

The Georgia material is neither abundant nor well preserved, but the identifications are unquestionable. A single scale was collected at Chimney Bluff, on Chattahoochee River, where it was associated with the abundant leafy twigs of *Araucaria bladenensis*, and, as mentioned under the discussion of that species, it renders probable the view that these cone scales and twigs were borne by the same Upper Cretaceous trees. A single specimen, entirely characteristic, was also obtained at the locality near Byron.

Occurrence.—Lower division of the Eutaw formation, Chimney Bluff, Chattahoochee County. (Collected by E. W. Berry.) Cusseta sand member of the Ripley formation, cut on Central of Georgia Railway, 1½ miles northeast of Byron, Houston County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Genus **BRACHYPHYLLUM** Brongniart.

BRACHYPHYLLUM MACROCARPUM FORMOSUM Berry.

Brachyphyllum macrocarpum Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 183.
Brachyphyllum macrocarpum Berry, idem, vol. 38, 1911, p. 420 (non Newberry, 1896).
Brachyphyllum macrocarpum formosum Berry, idem, vol. 39, 1912, p. 392, Pl. XXX.

Description.—Slender elongated twigs, pinnately branched, covered with medium-sized, crowded, appressed leaves, spirally arranged. Leaves bluntly pointed, relatively smooth, thick.

In the consideration of the various specimens that have been referred to *Brachyphyllum macrocarpum* Newberry a very considerable variation within certain fixed limits is at once obvious. This variation is usually one of size, but the more slender specimens are more elongated and smoother. This has been frequently noted by the writer and is commented upon in print by F. H. Knowlton,[1] who in discussing the later forms (from Wyoming) suggests that the species on the verge of extinction became smaller in its proportions.

In studying the material from the South Atlantic and Gulf States a constant difference in size was noticed by the writer. This may reflect a slight difference in climatic conditions, and all of the forms may be interpreted as the variations of a single species. In fact, one of Newberry's figures[2] of a Raritan specimen is approximately the same size as the forms from the Montana group of the West and is associated with the normal, stout, club-shaped type. That the variety has no particular stratigraphic significance is indicated by its abundance at a horizon as old as the basal part of the Tuscaloosa formation in Alabama and its presence in the Woodbine sand of Texas. In general, however, it occurs at later and more southern horizons than the type. This might be ascribed to the fact that only the slender and more elongated terminal twigs are preserved at these localities, but such an explanation is regarded as improbable, for the same reasoning should hold good for the areas where only the thicker twigs have been found.

The remains are generally much macerated and broken. The general proportions are decidedly different from the parent type. The leaves are slightly smaller and smoother and somewhat more elongated in their relative proportions and lack the apical papillæ and the convergent striæ. The new variety is much more graceful than the type in appearance and in its general aspect suggests the Lower Cretaceous genus Arthrotaxopsis. The most closely allied form appears to be one from the Albian of Portugal, described by Saporta[3] as *Brachyphyllum obesiforme elongatum.* There is also considerable resemblance to *Brachyphyllum crassicaule* Fontaine of the Patapsco formation in Maryland and Virginia. Remains of this new variety are associated with the type in Maryland; they are abundant throughout the Tuscaloosa of Alabama, ranging upward into the basal part of the Eutaw formation in both Alabama and western Georgia.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Genus **CUNNINGHAMITES** Presl.

CUNNINGHAMITES ELEGANS (Corda) Endlicher.

This species is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (pp. 24–25).

The Georgia specimens are from the locality near Byron, and though not nearly so large as the exceptional remains of this species from North Carolina, where many of the leaves are 6 centimeters or more in length, they are entirely typical, and with the associated cone scale of *Araucaria jeffreyi* serve admirably to indicate the probable horizon of the materials found near Byron, which are rather ambiguous lithologically and entirely unfossiliferous except for the three species of plants collected by Stephenson.

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[1] Bull. U. S. Geol. Survey No. 163, 1900, p. 29, Pl. IV, figs. 5 and 6.

[2] The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 51, Pl. VII, figs. 1–7. (See fig. 7.)

[3] Saporta, G. de, Flore fossile du Portugal, 1894, p. 176, Pl. XXXI, fig. 14.

Occurrence.—Cusseta sand member of the Ripley formation, cut on Central of Georgia Railway 1½ miles northeast of Byron, Houston County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Genus **SEQUOIA** Endlicher.

SEQUOIA REICHENBACHI (Geinitz) Heer.

This species is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (pp. 23–24).

Twigs of this species are rare at the Chimney Bluff locality but typical and common at McBrides Ford and Broken Arrow Bend. In this connection it is worthy of comment that Sequoia twigs are about the last fragments in floating vegetable débris to disintegrate, and their remains are frequently found in deposits in which the associated vegetation is reduced to an unrecognizable mass, as is so common in typically marine deposits.

Occurrence.—Lower division of the Eutaw formation, Chimney Bluff, McBrides Ford, Broken Arrow Bend, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Genus **TUMION** Rafinesque.

TUMION CAROLINIANUM Berry (?).

Tumion carolinianum Berry, Am. Jour. Sci., 4th ser., vol. 35, 1908, p. 383, figs. 1–3.

Description.—The following description is quoted from the work cited above:

> Leaves flat, somewhat rigid, linear-lanceolate, gradually tapering to a slender point from the broad but slightly contracted decurrent base, 25 to 30 millimeters long and up to 3 millimeters in greatest width, averaging somewhat more than 2 millimeters, arranged in a rather close spiral and apparently not distichous in habit. Mid vein absent, but in strong transmitted light a darker, i. e., more opaque, central band gradually dying out and presumably of vascular tissue is seen in the basal third of the leaf; this is not a surficial feature, however, since both the dorsal and ventral surfaces are unmarked centrally. In strong transmitted light the two stomatal bands characteristic of the modern species are fairly well shown after the leaves have been appropriately treated to reduce their opacity. These bands are narrow and their inner margin is just about one-fourth of the distance across the leaf, i. e., they are slightly nearer the margin than the median axis; they are confined to the lower surface and die out apically, becoming well marked proximally, and are made out with difficulty in the upper half of the leaf. The stomata are confined to the surface of these bands and are without orderly arrangement, usually not more than four in a transverse direction. These stomata are of medium size and strictly comparable with those of the existing American tumions with which comparisons have been made; the guard cells are slender and their orientation with respect to the leaf axis is indefinite, with apparently a prevailing tendency in the material examined to a position at right angles instead of one parallel with this axis, as in the case in the living material seen.

The presence of this species in Georgia is based upon three poorly preserved specimens from McBrides Ford that can not be identified with certainty. The leaves seem to be thicker than in the Carolina specimens, and though some of them show traces of the stomatal bands, always difficult to make out in material of this sort, others show suggestions of a midrib. It is believed, however, that this appearance is due to a slight keel developed in the basal part of the leaves, or to the method of preservation, for some of the leaves show longitudinal striations which would be explained in the same manner.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Class ANGIOSPERMÆ.

Subclass MONOCOTYLEDONÆ.

Genus DORYANTHITES gen. nov.

DORYANTHITES CRETACEA sp. nov.

Plate XVII, figure 3.

Description.—Leaves as preserved linear, presumably lanceolate above and sheathing below, 4.5 to 6 centimeters in width and preserved without any diminution in width for a length of 50 centimeters. Texture very coriaceous. Margins entire. Veins simple and parallel, immersed, considerably less than 1 millimeter apart. Leaves alike on both surfaces. In the hollows between the veins occur rows of small stomata with the guard cells all oriented in a direction parallel with the veins and equally numerous on both surfaces of the leaf. Leaf surface under the microscope appears finely striated parallel with the veins.

These curious remains, which call to mind the leaves of the Paleozoic Cordaites or some modern giant bromeliad, are not uncommon in the Upper Cretaceous. They were first discovered by the writer at Rockfish Creek, N. C., and were subsequently found 92 miles above Newbern, N. C., on Neuse River, both of which localities are in the Black Creek formation, and it is from the North Carolina specimens that the stomatal characters are described. Recently this same form was discovered in considerable abundance in the lower part of the Eutaw near Havana, Ala., and they are the most abundant fossils at the Georgia locality near Buena Vista.

Referring to the similarly appearing remains previously described it may be noted that Miquel[1] in 1853 described under the heading *Phyllitæ monocotylei* two sorts of parallel-veined leaf fragments from the Upper Cretaceous of Aachen. The first[2] he calls Yuccites? and the second, which suggests the fossils under discussion, he designates "Palma vel Yuccites?"

From the Valanginian of Portugal Heer[3] describes what he calls *Bambusium latifolium*, which is also suggestive of the American material.

Krasser[4] describes remains somewhat similar in appearance from the Cretaceous (Cenomanian) of Moravia as *Typhæloipum cretaceum*. These are somewhat smaller than the American forms and show transverse veinlets which are absent in the latter.

Smaller, but otherwise comparable Lower and Upper Cretaceous forms were named Eolirion by Schenk,[5] and similar older Mesozoic forms are commonly referred to the form genus Yuccites.[6] Perhaps the most similar fossils known are those referred to the genus Krannera[7] and fully described by Velenovsky, who does not, however, arrive at any satisfactory conclusion regarding their relationship, although he thinks they are cycadaceous. It seems undesirable to refer the Georgia material to Yuccites, for though they are similar to the more ancient remains so named, it is entirely improbable that they are congeneric with the Triassic type on which this genus was founded and such an identification would consequently be very misleading. Until the existing tropical Monocotyledonæ are more abundantly represented in our larger herbaria or more complete and decisive Cretaceous material is discovered the botanic affinity of these anomalous forms must remain undetermined. The name chosen indicates superficial resemblance and does not imply actual relationship with the modern genus Doryanthes of the order Liliales.

Little reliance can be placed upon similarity of appearance in dealing with fragmentary remains of this sort and the foregoing are mentioned merely as indicating the presence of undetermined monocotyledons of large size in the Cretaceous floras of the world.

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[1] Verh. Geol. kaart. Nederl., vol. 1, 1853, pp. 33–56, Pls. I–VII.

[2] Idem, Pl. I, fig. [illegible].

[3] Contributions à la flore fossile du Portugal, 1881, p. 22, Pl. XIX, figs. 1–3.

[4] Beiträge zur Kenntniss der fossilen Kreideflora von Kunstadt. Beitr. Pal. u. Geol. Oester.-Ungarns, vol. 10. 1896, p. 127 (15), Pl. XII (II), fig. 4.

[5] Palæontographica, vol. 19, 1869, p. 20.

[6] Schimper, W. P., and Mougeot, A., Monographie des plantes fossiles du grès bigarré de la chaîne des Vosges, 1844, p. 42.

[7] Velenovsky, J., Die Gymnospermen böhmischen Kreideformation, pt. 4, 1885, p. 1.

Occurrence.—Cusseta sand member of the Ripley formation, near Buena Vista, Marion County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Genus PHRAGMITES Trinius.

PHRAGMITES PRATTII Berry.

This species is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (p. 28).

Occurrence.—Lower division of the Eutaw formation, Broken Arrow Bend, Chattahoochee County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Subclass DICOTYLEDONÆ.

Order JUGLANDALES.

Family JUGLANDACEÆ.

Genus JUGLANS Linné.

JUGLANS ARCTICA Heer?

This form is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (p. 30). Its Georgia occurrence, which is the most southerly known, is based on a fragment which, as far as it goes, is characteristic and indicates the remarkable range of this species from 32° to 70° north latitude.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order SALICALES.

Family SALICACEÆ.

Genus SALIX Linné.

SALIX FLEXUOSA Newberry.

This form is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (pp. 32–33). In Georgia, though not especially abundant, characteristic leaves of this species are found from the base to the top of the Eutaw deposits which underlie the Tombigbee sand member.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chimney Bluff, Broken Arrow Bend, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

SALIX LESQUEREUXII Berry.

This species is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (p. 33). The Georgia remains were obtained near the top of the lower division of the Eutaw formation at Chimney Bluff on Chattahoochee River and are entirely typical.

Occurrence.—Lower division of the Eutaw formation, Chimney Bluff, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

SALIX EUTAWENSIS Berry.

Plate XIX, figure 3.

Salix eutawensis Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 193, Pl. XXII, figs. 1–11.

Description.—Leaves lanceolate in outline, somewhat falcate in some specimens, variable in size, from 5 to 12 centimeters in length and from 0.5 to 2.3 centimeters in greatest width, which is in the basal half of the leaf. Base lanceolate. Apex gradually narrowed to the attenuate tip. Margin entire for a short distance proximally, above which it is very finely dentate, even in the largest leaves collected. Petiole short and fairly stout. Midrib fairly stout, becoming thin in the apical part of the leaf, inclined to be curved or somewhat flexuous. Secondaries very fine and numerous, branching from the midrib at acute angles and curving upward, becoming in their terminal portions approximately parallel with the margin, sending short curved tertiaries to the marginal teeth and from secondary to secondary.

This species is abundant at the upper Tar River localities but has not been detected at any other localities in the Black Creek formation of North Carolina. It is common in the lower division of the Eutaw formation at Broken Arrow Bend on Chattahoochee River in Georgia, from which place the type material was collected. The Georgia material is more fragmentary than that from North Carolina but withstands drying out much better, the North Carolina material being preserved in a loose carbonaceous sandy clay which furnishes very poor museum specimens.

This typical willow leaf is quite modern in appearance, suggesting the existing *Salix nigra* Marsh, *Salix fluviatilis* Nuttall, or the Mexican *Salix bonplandiana* H. B. K., and is entirely distinct from any Cretaceous willows hitherto described. It approaches *Salix newberryana* Hollick [1] somewhat in general appearance but is much more elongate-lanceolate in outline and ranges to a much smaller size, besides showing other distinctive features. It also resembles certain European Tertiary willows, as, for example, *Salix denticulata, lavateri,* and *varians.* Certain fruits found associated with these leaves in North Carolina are believed to belong to the same species.

Occurrence.—Lower division of the Eutaw formation, Broken Arrow Bend, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order **URTICALES.**

Family **MORACEÆ.**

Genus **FICUS** Linné.

FICUS KRAUSIANA Heer.

Plate XIX, figure 4.

This species is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (p. 38). The Georgia material is somewhat more slender than the abundant material from South Carolina but agrees well with the type forms.

It is one of the most characteristic post-Raritan and pre-Ripley fossils in the Coastal Plain, the Georgia occurrence carrying it to a point within a few feet of the Tombigbee sand horizon on Chattahoochee River.

Occurrence.—Lower division of the Eutaw formation, Chimney Bluff, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

FICUS CRASSIPES (Heer) Heer.

Proteoides crassipes Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 110, Pl. XXXI, figs. 6–8a.
Ficus crassipes Heer, idem, vol. 6, Abth. 2, 1882, p. 70, Pls. XVII, fig. 9a, and XXIV, figs. 1, 2.
Ficus crassipes Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 79, Pl. XIII, fig. 3.
Ficus crassipes Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 172.

Description.—The following description was written by Heer in 1882:

> F. foliis coriaceis, lineari-lanceolatis, basi cuneatim attenuatis, integerrimis, nervo medio crasso, nervis secondariis obsoletis, petiolo longo-valido.

The leaves of this species as they occur in the southern Coastal Plain are narrowly lanceolate with gradually narrowed apex and base, about 15 centimeters in length by 2.5 centimeters in greatest width, and resemble *Ficus atavina* Heer in outline but are relatively narrower. The texture is coriaceous and the midrib and petiole are extraordinarily stout in many specimens. The secondary venation when seen is of the usual camptodrome type with relatively long, ascending, curved secondaries.

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[1] Hollick, Arthur, in Newberry, J. S., The flora of Amboy clay: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 68, Pl. XIV, figs. 2–7.

This species was described originally from the Atane beds of western Greenland, the first rather fragmentary specimens collected having suggested the genus Proteoides. It was subsequently recorded from the Dakota sandstone of Kansas by Lesquereux. In the Atlantic Coastal Plain it is found in the Magothy and Black Creek formations, including the Middendorf member of the latter, and it is especially common in clays of the Tuscaloosa formation of Alabama.

Occurrence.—Lower division of the Eutaw formation, Chimney Bluff, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

FICUS GEORGIANA sp. nov.

Plate XX, figure 1.

Description.—Leaf ovate-lanceolate in outline, gradually tapering to an acute point. Proximately the leaf is broadly and abruptly rounded to a point within 2 to 3 millimeters of the midrib, thence decurring as a narrow wing 1 millimeter or less in width and preserved for a distance of 1 centimeter. Length, about 17 centimeters. Greatest width, which is near the base of the leaf, 4.5 centimeters. Midrib fairly stout. Margin entire. Secondaries thin, parallel, and numerous, branching from the midrib at angles of about 50° and curving upward distally, camptodrome.

This species suggests *Ficus beckwithii* Lesquereux of the Dakota sandstone and *Ficus krausiana* Heer, which is abundant in the Upper Cretaceous of America from Marthas Vineyard to Alabama and which occurs also in the Dakota sandstone and at the type locality in the Cenomanian of Europe, Moletein, Moravia. The Georgia plant is perfectly distinct from these species, however, the most conspicuous difference being its broadly rounded base.

Occurrence.—Cusseta sand member of the Ripley formation, near Buena Vista, Marion County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

FICUS OVATIFOLIA Berry.

Plate XIX, figures 5–7.

Ficus ovata Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 70, Pl. XXIV, figs. 1–3 (non Don, 1802–3).

Ficus ovatifolia Berry, Bull. Torrey Bot. Club, vol. 36, 1909, p. 253.

Description.—Leaves ovate in outline, extended above into a narrow, usually pointed apex. Length 8 to 12 centimeters. Greatest width, which is in the basal part of the leaf, 4 to 7 centimeters. Base broadly rounded and in many specimens slightly decurrent. Margins entire. Primaries, three from the base, the midrib somewhat stouter than the lateral primaries. Secondaries camptodrome.

This species is closely allied to the Raritan species *Ficus woolsoni* Newberry,[1] differing primarily in its greater elongation and in the tendency of the former to a cordate outline.

The Georgia Cretaceous furnishes three species of pinnately veined lanceolate fig leaves, the present species alone representing that other important section of Ficus with broader leaves and palmate venation. *Ficus ovatifolia* was described originally from the Raritan formation of New Jersey. It is present in the Black Creek formation of North Carolina and very probably in the Tuscaloosa formation of Alabama. The Georgia representatives are not rare at the McBrides Ford locality. One of them (Pl. XIX, fig. 6) shows an unusual variation in the character of the apex, which in this specimen is diagonally retuse.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

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[1] Newberry, J. S., The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 70; Pls. XX, fig. 3; XXIII, figs. 1–6.

Order RANALES.

Family MAGNOLIACEÆ.

Genus MAGNOLIA Linné.

MAGNOLIA BOULAYANA Lesquereux.

Plate XX, figure 5.

Magnolia boulayana Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 202, Pl. LX, fig. 2.
Magnolia glaucoides Hollick, Bull. Torrey Bot. Club, vol. 21, 1894, p. 60, Pl. CLXXV, figs. 1 and 7.
Magnolia glaucoides Smith, On the geology of the Coastal Plain of Alabama, 1894, p. 348.
Magnolia glaucoides Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 74, Pl. LVII, figs. 1-4.
Magnolia boulayana Knowlton, Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, p. 318.
Magnolia glaucoides Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 67, Pls. XIX, fig. 6; XX, fig. 6.
Magnolia boulayana Berry, Bull. Torrey Bot. Club, vol. 36, 1909, p. 254.
Magnolia boulayana Berry, idem, vol. 37, 1910, p. 23.

Description.—Leaves narrowly elliptical in outline, unusually uniform in size and shape, 8.5 to 13 centimeters in length and 3.5 to 4.5 centimeters in width. Apex usually bluntly rounded, in some specimens acute. Base matching the apex. Petiole fairly stout, 3 to 4 centimeters in length. Midrib fairly stout. Secondaries slender, many obsolete, about 11 pairs, equidistant, parallel, camptodrome, branching from the midrib at an angle of about 40°. Tertiaries, when seen, transverse. Texture coriaceous.

This species was described originally from the Dakota sandstone of Kansas. Subsequently Newberry described the Raritan remains, which are abundant at the Woodridge, N. J., locality, as a new species, *Magnolia glaucoides*, and it has been kept distinct by Hollick, who recognized, however, its practical identity with the form from the Dakota sandstone. There can be no question but that they belong to the same species, and it seems probable that *Magnolia vaningeni* described by Hollick[1] should be referred to the same species.

In addition to the localities already mentioned this species is found on Marthas Vineyard and Long Island, also in the Tuscaloosa formation of Alabama, and in the Woodbine sand of Texas. The Georgia occurrence is based upon the admirable specimen figured, and forms a link in the chain which serves to connect the eastern and Dakota sandstone floras through the Gulf area.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

MAGNOLIA CAPELLINII Heer.

Plate XX, figure 6.

Magnolia capellinii Heer, Phyllites crétacées du Nebraska, 1866, p. 21, Pl. III, figs. 5 and 6.
Magnolia capellinii Heer, Flora fossilis arctica, vol. 3, Abth. 2, 1874, p. 115, Pl. XXXIII, figs. 1-4.
Magnolia capellinii Heer, idem, vol. 6, Abth. 2, 1882, p. 90, Pls. XXIV, figs. 3-5; XXV, figs. 1-3; and XLV, fig. 1.
Magnolia capellinii Velenovsky, Die Flora der böhmischen Kreideformation, pt. 2, 1883, p. 20, Pl. VII, figs. 8 and 9.
Magnolia capellinii Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 203, Pl. LXVI, fig. 1.
Magnolia capellinii Hollick, Trans. New York Acad. Sci., vol. 12, 1893, p. 234, Pl. VI, fig. 6.
Magnolia capellinii Dawson, Trans. Roy. Soc. Canada, 1st ser., vol. 11, sec. 4, 1894, p. 63, Pls. XI, fig. 49, and XIII, fig. 49a.
Magnolia capellinii Hollick, Bull. Geol. Soc. America, vol. 7, 1895, p. 13.
Magnolia capellinii Hollick, Bull. New York Bot. Garden, vol. 3, 1904, p. 413, Pl. LXXVIII, fig. 3.
Magnolia capellinii Berry, Bull. Torrey Bot. Club, vol. 31, 1904, p. 76, Pl. III, fig. 3.
Magnolia capellinii Berry, Ann. Rept. State Geologist New Jersey for 1905, 1906, p. 138.
Magnolia capellinii Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 63, Pl. XVII, figs. 3 and 4.
Magnolia capellinii Berry, Bull. Torrey Bot. Club, vol. 34, 1907, p. 195, Pl. XII, figs. 4 and 5.

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[1] Bull. Torrey Bot. Club, vol. 21, 1894, p. 61, Pl. CLXXV, fig. 6.

Description.—Heer's original description, written in 1866, is as follows:

M. foliis coriaceis, late ovalibus, integerrimis, nervis secundariis angulo acuto egredientibus, curvatis camptodromis.

These leaves vary considerably in size, averaging about 13 centimeters in length by 7 centimeters in width. Outline broadly ovate, the base and apex generally equally pointed, although a few specimens have a somewhat obtuse apex. The texture is coriaceous or subcoriaceous. Midrib and petiole stout. Secondaries, usually seven or eight alternate or subopposite pairs, at regular intervals, approximately parallel, camptodrome.

This widespread species in some of its forms very closely approaches the less narrow and apically extended forms of *Magnolia speciosa* Heer. Ordinarily, however, the latter species may be readily detected by its relatively narrower form with produced apex and decurrent base.

This species was described originally from the Dakota sandstone by Heer and has been detected at a large number of localities of homotaxial age in both the Greenland Cretaceous and in that of the Pacific Coast. In the Atlantic Coastal Plain it characterizes the Magothy formation and is present in the Black Creek formation of North Carolina and the Tuscaloosa formation of Alabama. It was doubtfully recorded from the Raritan formation of New Jersey by Lesquereux in 1878, but it has never been detected in the abundant collections of Raritan plants studied either by Newberry or the writer and is not at present admitted to be a member of the Raritan flora. The Georgia occurrence is based on the specimen figured, a broadly ovate leaf, about 13.5 centimeters in length by 6.5 centimeters in width, of coriaceous texture, which is poorly preserved in the sandy clay at McBrides Ford. It approaches some of the forms of *Magnolia speciosa* in appearance, and perhaps it may be more intimately related to the latter species, which is very abundant in the Tuscaloosa formation. In either case the stratigraphic conclusions which may be drawn from the material are identical.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry).

Collections.—U. S. National Museum.

Genus **MENISPERMITES** Lesquereux.

MENISPERMITES VARIABILIS sp. nov.

Plate XXI, figures 1–4.

Description.—Leaves of medium size, trilobate, but variable in shape. Length about 9 or 10 centimeters. Greatest width, which is from tip to tip of the laterally directed lobes, as much as 16 centimeters in one specimen. Lobes broad and separated by wide shallow sinuses. Margin entire but in some specimens scalloped, the scallops rounded and nearly equilateral, separated by acute sinuses. Base peltate, broadly rounded as in Aspidiophyllum or with a cordate sinus which does not, however, reach the top of the petiole. Primaries stout, three or four in number, palmately divergent from the peltate base, three of them generally equal in caliber. Secondaries slender and numerous, some apparently camptodrome and others craspedodrome.

This peculiar species was apparently inequilateral and variable in outline, but unfortunately no complete specimens were collected, though the remains are not uncommon. They are markedly distinct from any Cretaceous forms hitherto described and add another curious element to the remarkable assemblage found in the lower division of the Eutaw formation of Georgia, which includes the gigantic specimens of Manihotites and the no less curious Androvettia and Doryanthites.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order **EUPHORBIALES.**

Family **EUPHORBIACEÆ.**

Genus **MANIHOTITES** Berry.

MANIHOTITES GEORGIANA Berry.

Plates XXII, XXIII; and XXIV, figures 4 and 5.

Manihotites georgiana Berry, Bull. Torrey Bot. Club, vol. 37, p. 507, figs. 1 and 2, 1910.

Description.—Leaves of extraordinarily large size, 36 to 48 centimeters across, palmately and deeply lobate, the main lobes dichotomously sublobate. Base missing, probably peltate. Margins entire, more or less undulate. Texture coriaceous. Venation coarse. Five or six stout primaries diverge at acute angles from the top of the petiole and fork dichotomously about 5 or 6 centimeters above their base at angles of 30° to 50°. These branches may again fork dichotomously in a distance of 4 to 6 centimeters, or may not give off any branches, or the branches may be clearly subsidiary in size and run to the apex of a subordinate lobe. There are a sparse number of relatively fine secondaries, which diverge at angles of about 45° or more and are apparently camptodrome. In each of the large specimens a straight vein of secondary size runs directly to the base of a single main sinus. It is possible that this vein diverges along the margin in a vein which forms a marginal hem, as in the sinuses of lobed sassafras leaves, but such a vein can not be made out, although at one point there is such a marginal vein connected with the main venation by straight transverse tertiaries. Deep and narrow but rounded sinuses approach within 3 to 5 centimeters of the base and divide the leaf into five or more major lobes; these are subdivided by more or less deep sinuses of a similar character into inequilateral, ovate lanceolate, obtusely pointed subordinate lobes.

It seems probable from the manner in which the extreme base is torn away in the two nearly complete specimens collected that this base was peltate and comparable to those leaves of the modern Manihot, Podophyllum, Jatropha, and similar forms, which are inequilaterally peltate. There was considerable variability in the lobation, as is clearly shown by these two nearly complete leaves, which were found close together in the small leaf-bearing clay lens at McBrides Ford. It seems decidedly probable that these two leaves were from a single plant, for it is very unlikely that two separate leaves of the same degree of preservation would have found their way out in the Cretaceous sea and have come to rest within a few inches of each other in this very restricted clay lens, which was not over a few feet in diameter and some miles from the Cretaceous shore. One leaf has the margins broadly rounded and each main lobe divided into two nearly equal subordinate lobes; in the other leaf these subordinate lobes are subdivided in a like manner and some of these are again sublobate.

Remains of these curious leaves were first encountered at the plant locality near Buena Vista, where they occur in a very fragmentary state, the most complete specimens being the counterparts figured in Plate XXIV, figures 4 and 5. A very small fragment which is identical with or closely related to these forms had been previously collected from the Black Creek formation along Neuse River in North Carolina but had not been recognized. Though these leaves differ in important particulars, notably in having the primaries arranged palmately and the lamina in the forks of the veins less abbreviated, they are similar to and possibly congeneric with *Fontainea grandifolia*, described by Newberry [1] from the Raritan formation in New Jersey. The incomplete nature of the material upon which this species and genus was based makes any detailed comparisons impossible. In the New Jersey species the entire lamina is cut out in the sinuses for a distance of several centimeters.

In discussing the New Jersey plants Newberry [2] compared them with *Haliserites reichii*,[3] reproducing Sternberg's figure. This plant came from the Cretaceous greensand of Niederschoena, Saxony (Cenomanian), and was discovered by Reich, who named it *Fucoides dicho-*

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[1] The flora of the Amboy clays. Mon. U. S. Geol. Survey, vol. 26, 1896, p. 96, Pl. XLV, figs. 1–4.
[2] Op. cit., p. 96, Pl. XLV, fig. 5.
[3] Sternberg, Flora der Vorwelt, vol. 2, 1833, p. 34, Pl. XXIV, fig. 7.

tomus. Sternberg referred it to Haliserites because of its fancied resemblance to a recent alga, *Haliseris polypodoides* Agardh. Though much smaller than the American species of Fontainea, the Saxon plant is hardly a seaweed, and is closely comparable with the American genus.[1]

A similar form, more nearly the size of Fontainea, is figured by Bronn [2] and retained in Haliserites, although Rossmassler and Cotta referred it to Chiropteris. Schimper[3] refers it to Delesseria, comparing it with the modern *Delesseria ruscifolia* Agardh, as well as with Haliseris, and more recently Rothpletz [4] has recognized its angiospermous affinities and renamed it *Phyllites reichi*. Still another similar plant is one described by Velenovsky from the Cenomanian of Bohemia as *Aralia furcata*[5] and compared with the modern genera Jatropha, Vitex, Cussonia, and like forms. It is hardly an Aralia, and is very similar to the forms previously mentioned.

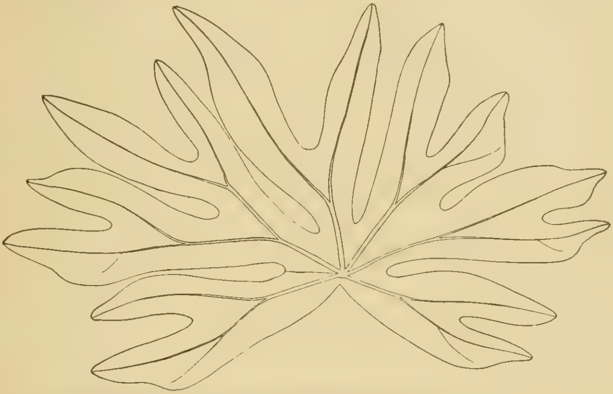

FIGURE 2.—Restoration of the leaf of Manihotites georgiana figured in Plate XXII. (One-eleventh natural size.)

It might be added that Newberry compared his fossils with the leguminous genera Hymenæa and Bauhinia and regarded the genus Sapindopsis from the Lower Cretaceous of Maryland and Virginia as related to the Raritan plant. These are, however, entirely distinct and unrelated.

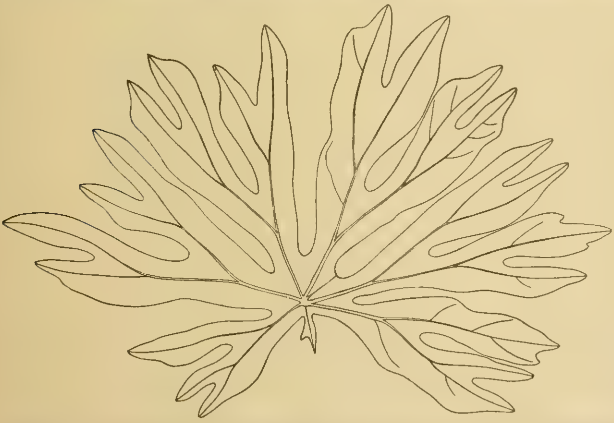

FIGURE 3.—Restoration of the leaf of Manihotites georgiana figured in Plate XXIII. (One-fifteenth natural size.)

A number of modern genera have leaves more or less suggestive of this Upper Cretaceous species, for example, Podophyllum, Jatropha, Cecropia, and various tropical Araliaceæ. The fossils have been carefully compared with these and with a number of other modern genera. They are closest, however, to certain modern species of Manihot, and it is believed that the remarkably variable leaves of the latter furnish a satisfactory clue to the relationship of this Cretaceous form, for no other comparable modern genus shows similar wavy margins and inequilateral rounded lobes. The venation is also very similar. Figures 2 and 3 show reduced restorations of the fossil leaves figured on Plates XXII and XXIII.

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[1] Rothpletz in 1896 recognized the dicotyledonous nature of this species and renamed it *Phyllites reichi*. (Zeitschr. Deutsch. geol. Gesell., vol. 48, p. 904.)

[2] Lethæa geognostica, Pl. XXVIII, fig. 1.

[3] Paléontologie végétale, vol. 1, 1869, p. 178.

[4] Zeitschr. Deutsch. geol. Gesell., vol. 48, 1896, p. 904.

[5] Die Flora der böhmischen Kreideformation, pt. 3, 1884, p. 13, Pl. IV, fig. 1 (*Aralia elegans*).

The modern species of Manihot Adanson number between 80 and 100 and are nearly all endemic in tropical South America, the great majority occurring in Brazil, which has more than 70 species. There are one or two species in Argentina, and the remaining species occur in Peru and Guiana and northward through Central America into Mexico. According to Tracy[1] the various cultivated varieties of Manihot (cassava), though natives of the Tropics, can be grown where the growing season lasts 10 or 11 months, as in parts of the Gulf States. Light frost, however, and even continued cool weather entirely stop growth. Even in the Tropics the best growth is made in coastal regions, so that if the present fossil species is assumed to have required a similar habitat it would serve to corroborate the ecologic evidence furnished by the other members of the Georgia Upper Cretaceous flora.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Order **RHAMNALES.**

Family **RHAMNACEÆ.**

Genus **PALIURUS** Linné.

PALIURUS UPATOIENSIS sp. nov.

Plate XXI, figures 5 and 6.

Description.—Leaves small, obovate, 3 to 4 centimeters in length by 1.3 to 1.6 centimeters in greatest width, which is about halfway between the apex and the base. Apex broadly and evenly rounded. Base narrowly decurrent. Margin entire. Primaries three in number from the extreme base, about equal in caliber, acrodrome. Secondaries not made out. Texture rather coriaceous.

This species is clearly distinct from any previously described Cretaceous forms, although it resembles somewhat *Paliurus obovatus* Lesquereux, of the Dakota sandstone of the West and *Paliurus populifolius* Berry of the Magothy formation of New Jersey. In outline these leaves are not unlike some of the less orbicular leaves of Pistia found in the Black Creek formation of North Carolina, but the venation is of a different character and the broad sheathing base found in Pistia is wanting.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Genus **ZIZYPHUS** Linné.

ZIZYPHUS LAURIFOLIUS sp. nov.

Plate XXI, figure 7.

Description.—Leaves lanceolate, 9 to 10 centimeters in length by about 2 centimeters in greatest width, about equally pointed at the apex and the base. Margin entire. Primaries three in number from the extreme base, the midrib being the stoutest. Secondaries for the most part not seen, though a few, acutely branching and camptodrome, from the outside of the lateral primaries can be made out.

This species is entirely distinct from any heretofore described from the Cretaceous, although it resembles somewhat *Zizyphus cliffwoodensis* Berry from the Magothy formation of New Jersey.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

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[1] Tracy, F. M., Farmers' Bull. No. 167, U. S. Dept. Agr., 1903.

Order THYMELEALES.

Family LAURACEÆ.

Genus CINNAMOMUM Blume.

CINNAMOMUM NEWBERRYI nom. nov.

Plate XXI, figures 9–11.

Cinnamomum sezannense Heer, Flora fossilis arctica, vol. 6, Abth. 2, 1882, p. 77, Pls. XIX, fig. 8, and XXXIII, figs. 11 and 12 (non Watelet).

Cinnamomum sezannense Heer, idem, vol. 7, 1883, p. 30, Pl. LXI, fig. 1a (non Watelet).

Cinnamomum sezannense Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 107, Pl. XII, fig. 7 (non fig. 6, which is a leaf of *Cinnamomum membranaceum* (Lesquereux) Hollick).

Cinnamomum sezannense Dawson, Trans. Roy. Soc. Canada, 1st ser., vol. 11, sec. 4, 1894, p. 64, Pl. XIII, fig. 58 (non Watelet).

Cinnamomum sezannense Hollick, Bull. Torrey Bot. Club, vol. 21, 1894, p. 53, Pl. CLXXX, figs. 5 and 7 (non Watelet).

Cinnamomum intermedium Smith, On the geology of the Coastal Plain of Alabama, 1894, p. 348 (nomen nudum).

Cinnamomum intermedium Newberry, The flora of the Amboy clays: Mon. U. S. Geol. Survey, vol. 26, 1896, p. 89, Pl. XXIX, figs. 1–8 and 10 (non Ettingshausen).

Cinnamomum sezannense Penhallow, Trans. Roy. Soc. Canada, 2d ser., vol. 8, sec. 4, 1902, p. 46 (non Watelet).

Cinnamomum sezannense Hollick, Fifty-fifth Ann. Rept. N. Y. State Mus. for 1901, 1903, p. r50.

Cinnamomum intermedium Berry, Rept. State Geologist, New Jersey, for 1905, 1906, p. 139, Pl. XX, figs. 2–6 (non Ettingshausen).

Cinnamomum intermedium Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 179, Pl. VII, figs. 3 and 4 (non Ettingshausen).

Cinnamomum intermedium Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 74, Pls. XXIX, fig. 7, and XXX, figs. 1 and 2 (non Ettingshausen).

Cinnamomum intermedium Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 27 (non Ettingshausen).

Description.—The name of this important American Cretaceous species is unfortunately preoccupied, as it was used in 1887, nine years before Newberry's work appeared, by the late Baron Ettingshausen [1] for an early Tertiary species from New Zealand. A new name is therefore necessary, and the writer feels that none can be more appropriate than one which honors the memory of one of America's pioneer paleobotanists.

Leaves subcoriaceous, lanceolate to ovate-lanceolate in outline, varying greatly in size and consequently in appearance. Apex short, pointed or more or less narrowly extended. Base broad, narrowed to the petiole. Primaries three, usually suprabasilar. This species is primarily distinguished from *Cinnamomum heerii* Lesquereux by its relatively narrower form and acute base. The Georgia material is not uncommon, but is for the most part extremely fragmentary. The single complete leaf is of the short type like that shown in Newberry's figure 10,[1] or like the leaves from the Arctic and from the Dakota sandstone which have usually been referred to *Cinnamomum sezannense* Watelet. That they are not in the slightest degree related to this European basal Eocene type may be readily seen by a comparison of the American Cretaceous material with the figures of the true *Cinnamomum sezannense* as given by Watelet, Saporta, and others.[2]

The present species, as here revised according to the foregoing citations, has a remarkable range in the earlier half of the Upper Cretaceous. The Raritan formation of New Jersey is the oldest horizon from which it is known. Above the Raritan horizon it occurs in the Atane and Patoot beds of Greenland, in the Magothy formation from Long Island to Maryland, in the Black Creek formation of North Carolina, in the Middendorf member of the Black Creek of South Carolina, in the Tuscaloosa formation of Alabama, where it is especially abundant at certain localities, and in the Dakota sandstone of Kansas. It appears to be present in the Upper Cretaceous of the Pacific coast on Vancouver Island, and is probably represented in the Texas remains of Cinnamomum recorded by Knowlton [3] from the Woodbine sand in

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[1] Denkschr. K. Akad. Wiss. Wien, Math.-nat. Kl., vol. 53, 1887, p. 166, Pl. IV, figs. 20–22.

[2] Watelet, A., Description des plantes fossiles bassin de Paris, 1866, Pl. L, fig. 2. Saporta, G. de, Flore fossile de Sézanne, 1865, Pl. VIII, fig. 5; Végétation à l'époque des marnes heersiennes de Gelinden, 1873, Pl. VI, figs. 5, 6; Revision de la flore heersienne de Gelinden, 1878, Pl. IX, figs. 2–6. Friedrich, P. A., Beiträge zur Kenntniss der Tertiärflora der Provinz Sachsen, 1883, Pl. I, fig. 5.

[3] Hill, R. T., Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 7, 1901, p. 317.

Cooke County, Tex. Although not known from Europe the forms from the Cenomanian of Bohemia which Velenovsky describes as *Aralia daphnophyllum*[1] are very similar to this American species.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

CINNAMOMUM HEERII Lesquereux?

Plate XXI, figure 8.

Cinnamomum heerii Lesquereux, Am. Jour. Sci., 2d ser., vol. 27, 1859, p. 361.

Cinnamomum heerii Lesquereux, Trans. Am. Philos. Soc., vol. 13, 1869, p. 431, Pl. XXIII, fig. 12.

Cinnamomum heerii Lesquereux, The Cretaceous flora, 1874, p. 84, Pl. XXVIII, fig. 11.

Daphnogene heerii Lesquereux, Ann. Rept. U. S. Geol. and Geog. Survey Terr. for 1874, 1876, p. 343.

Cinnamomum heerii Lesquereux, The Cretaceous and Tertiary floras, 1883, p. 54.

Cinnamomum heerii Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 105, Pl. XV, fig. 1.

Cinnamomum heerii Newberry, The later extinct floras of North America: Mon. U. S. Geol. Survey, vol. 35, 1898, p. 100, Pl. XVII, figs. 1–3.

Cinnamomum heerii Knowlton, in Hill, Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 7, 1901, p. 318, Pl. XXXIX, fig. 5.

Cinnamomum heerii Kurtz, Revista Mus. La Plata, vol. 10, 1902, p. 52.

Cinnamomum heerii Berry, Ann. Rept. State Geologist New Jersey for 1905, 1906, p. 139.

Cinnamomum heerii Berry, Bull. Torrey Bot. Club, vol. 33, 1906, p. 179.

Cinnamomum heerii Berry, idem, vol. 34, 1907, p. 200, Pl. XIII, figs. 2 and 3.

Cinnamomum heerii Hollick, The Cretaceous flora of southern New York and New England: Mon. U. S. Geol. Survey, vol. 50, 1907, p. 75, Pl. XXX, figs. 5 and 6.

Description.—Leaves coriaceous, entire, ovate in outline, more or less attenuated apically. Base broadly rounded. Primaries three, stout, suprabasilar. Secondaries camptodrome.

The exact status of this species is made out with difficulty. In typical specimens it is clearly distinct from *Cinnamomum Newberryi* Berry in its more regular outline and venation, broader form, more rounded base, and stouter suprabasilar primaries. Other remains have been referred to *Cinnamomum heerii* which are not typical in some of these distinctive characters, and the well-known variation of the leaves of Cinnamomum renders a satisfactory solution of the problem difficult. This species was doubtfully recorded from the Raritan formation by Lesquereux in 1878, but it has not been detected at this horizon either by Newberry or by the writer and is not admitted as a member of the Raritan flora. It does, however, characterize the somewhat younger beds represented in the west by the Dakota sandstone and the Woodbine sand and in the Coastal Plain by the Magothy formation of the north and the Black Creek and Tuscaloosa formations of the south. In the Georgia area it is represented by fragments showing the coriaceous texture, broad base, and suprabasilar primaries of the species. It occurs at McBrides Ford.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Genus **MALAPOENNA** Adanson.

MALAPOENNA HORRELLENSIS Berry.

Malapeonna horrellensis Berry, Bull. Torrey Bot. Club, vol. 37, 1910, p. 198, Pl. XXIV, figs. 1–9.

Description.—The following description is given in the work cited above:

> Leaves ovate-lanceolate, about 8 centimeters long by 2.5 centimeters in greatest width; broadest at the evenly rounded or slightly acute base, narrowing gradually upward, the apex narrow and extended but obtusely pointed. Leaf substance thin but persistent, evidently coriaceous in life, as these leaves occur abundantly at a locality where all the vegetable remains except the resistant Araucaria, Cunninghamites, and Pistia were evidently thoroughly macerated before entombment. Secondaries four to six pairs, subopposite, curved upward, camptodrome, branching from the midrib at an acute angle, the lowest pair branching from the top of the petiole and extending upward halfway

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[1] Velenovsky, J., Die Flora der böhmischen Kreideformation, pt. 1, 1882, p. 23, Pls. V, figs. 5–8, 10; VI, figs. 1–5.

to the apex or farther, giving the leaf a triple-veined appearance. Perhaps they should be termed lateral primaries, although they are much finer than the fairly stout midrib. The next pair of secondaries branch at a less acute angle, a considerable distance above the base, one-third to one-half the distance to the apex. Tertiary venation typically lauraceous.

This species is markedly distinct from the species of lauraceous leaves hitherto described in its rounded base, the only genus of this family with such a character being Cinnamomum. The present species may possibly be confused with *Cinnamomum heerii* when only the basal part of the leaf is found, but the general proportions and characters of the whole leaf are perfectly distinct.

It is common at several localities in the upper beds of the Black Creek formation in North Carolina and is represented in the collections from the Eutaw formation of Alabama by several forms as yet unstudied. The Georgia occurrence is based on fragmentary material from Broken Arrow Bend on Chattahoochee River.

The genus Malapoenna has more than one hundred existing species, chiefly of the Oriental tropics, and is well represented in the fossil state from the Dakota and Magothy formations upward. It is especially well represented in the Paleocene of Europe and in the Shoshone group of America. Of the two species in the Dakota sandstone of the West, one occurs in the Tuscaloosa formation at Cottondale, Ala., and the other in the Magothy formation of New Jersey.

Occurrence.—Lower division of the Eutaw formation, Broken Arrow Bend, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order UMBELLALES.

Family ARALIACEÆ.

Genus ARALIA Linné.

ARALIA EUTAWENSIS sp. nov.

Plate XX, figure 7.

Description. -Leaves relatively small in size, palmately quinquelobate. Length about 8 centimeters. Greatest width 8 to 9 centimeters across the basal lobes, which are directed laterally; the other three lobes are directed upward. Margin entire. Lobes obtusely pointed, inclined to be parallel sided, divided not quite halfway to the base, the upper two sinuses narrow, the lateral sinuses more open and obtusely rounded. Base slightly decurrent. Primaries five in number, diverging from the base or just above it, equal in caliber, and slightly flexuous in their course. Secondaries not made out.

This species greatly resembles the leaves from the Magothy formation of New Jersey and from the Black Creek formation of North Carolina, which have been identified with *Aralia newberryi* Berry of the Raritan formation. In fact, a careful study of a considerable series of these forms will probably result in uniting these Magothy and Black Creek forms with the present species as distinct from the Raritan species.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

Order MYRTALES.

Family MYRTACEÆ.

Genus EUCALYPTUS L'Héritier.

EUCALYPTUS ANGUSTA Velenovsky.

Plate XX, figures 2-4.

This species is described in the section of the report dealing with the Upper Cretaceous flora of South Carolina (pp. 55-56). The Georgia occurrences include well-marked remains from

Buena Vista, which are here figured, and more fragmentary but entirely typical material from McBrides Ford.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.) Cusseta sand member of the Ripley formation, Buena Vista, Marion County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

Order **ERICALES.**

Family **ERICACEÆ.**

Genus **ANDROMEDA** Linné.

ANDROMEDA NOVÆCÆSAREÆ Hollick.

Plate XXIV, figure 1.

This species is described in the section of this report dealing with the Upper Cretaceous flora of South Carolina (pp. 58–59). It was one of the few species whose leaves successfully resisted maceration in the shallow shoreward deposits known as the Cusseta sand member of the Ripley formation of Georgia. It occurs at Buena Vista in association with *Araucaria bladenensis.*

Occurrence.—Cusseta sand member of the Ripley formation, Buena Vista, Marion County. (Collected by L. W. Stephenson.)

Collections.—U. S. National Museum.

ANDROMEDA CRETACEA Lesquereux?

Plate XXIV, figure 2.

Andromeda cretacea Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 117, Pls. XVII, figs. 17 and 18, and XXIV, fig. 5.

Description.—Leaf small, thin, lanceolate, acuminate, with a thin midrib. Length about 3.5 centimeters. Greatest width about 7.5 millimeters, about halfway between the apex and the base. Secondaries not seen in the Georgia material. In the type material from Kansas they are parallel, nearly equidistant, much curved near the margins, camptodrome.

This species was based upon rather fragmentary material from the Dakota sandstone of Ellsworth County, Kans., and the Georgia material, which is referred with some hesitation to this species, is about as poor as the type material. It has not heretofore been collected outside the type locality, although similar forms which are probably of this species are present in the writer's collections from the Tuscaloosa formation of western Alabama.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

ANDROMEDA WARDIANA Lesquereux.

Plate XXIV, figure 3.

Andromeda wardiana Lesquereux, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 119, Pl. LXIV, fig. 17.

Description.—Leaf elliptical in outline, entire. Apex and base equally narrowed but the apex bluntly rounded. Length 5.3 centimeters. Greatest width, which is halfway between the apex and the base, 2.3 centimeters. Midrib thin. Secondaries not made out. In the type they are thin, diverging at an angle of about 40° and camptodrome.

The type material came from the Dakota sandstone of Ellsworth County, Kans. The Georgia material shows a leaf which is a trifle larger but which in its general proportions and outline is identical with the western form, and there can be no doubt of their identity.

It is quite possible, in fact probable, that this species is not distinct from *Andromeda tenuinervis* Lesquereux,[1] which, if the form referred to it by Hollick[2] is correctly identified, approaches it closely in size. The two differ somewhat in texture and in the degree of acuteness of the apex, but whether these features are of specific value or not is an open question.

Occurrence.—Lower division of the Eutaw formation, McBrides Ford, Chattahoochee County. (Collected by E. W. Berry.)

Collections.—U. S. National Museum.

BOTANIC CHARACTER OF THE FLORA.

The Cretaceous flora of Georgia as disclosed by the collections studied is relatively small, embracing only 32 determinable species. That it presents but a meager picture of the actual plant covering of the adjacent land is obvious in many ways. It need only be contrasted with the abundant floras of near-by more or less homotaxial deposits, such as the Tuscaloosa formation of northwestern Alabama or the Middendorf arkose member of the Black Creek formation to the northeast in South Carolina, to emphasize the disparity in the number of specific forms. This is believed to be due not to any relative paucity in the contemporaneous vegetation of the Cretaceous Piedmont area of Georgia, but to the character of the sediments and the opportunities they afforded for preservation of leaf remains. All the Upper Cretaceous deposits of Georgia are marine in character, and though some, like the Cusseta and Providence sand members of the Ripley formation, were evidently deposited in shallow water near shore, current or wave action seems to have been comparatively violent. Thus the vegetable débris which was floated into the Cretaceous sea was much triturated before entombment or thoroughly oxidized in the loose matrix afterwards. That such débris was present in the water is evident wherever local lenses of clay were laid down in quieter waters. It is from such relatively insignificant lenses that all the flora now available is derived, and the character of these remains, both as to their condition of preservation and with regard to the forms represented, fully substantiates the preceding statements. The areas in which these deposits merged into their estuarine or fluviatile phases, and in which plant fossils were probably better preserved, have been entirely destroyed by subsequent erosion, as might be expected, or else the Cretaceous shore line was an almost continuous sand beach without any of the considerable reentrants which usually play so prominent a part in preserving the records of ancient floras. The most prolific Cretaceous plant locality in Georgia is that at McBrides Ford, near the landward margin of the Eutaw formation, and here the total number of recognizable forms is only 19. (See p. 101.)

Though these are not all forms whose existing representatives belong to the strand flora or to that which flourished in immediate proximity to the coast, it is noticeable that nearly all are forms with coriaceous foliage, like the conifers, of which there are four species, and like the species of Andromeda, Ficus, Eucalyptus, and Magnolia. Furthermore the types represented which may be regarded as inland forms are species that probably inhabited stream bottoms. These are not abundant in individuals and are usually much macerated and broken.

The next locality in point of abundance of forms is that at Chimney Bluff, where small lenses of clay at the top of the Eutaw formation, comparable in size with those at the preceding locality near the base of the formation, have yielded seven species, three of which are conifers, two willows, and two coriaceous fig leaves. The six species recorded from near Buena Vista, the five species from Broken Arrow Bend, and the three species from the locality near Byron are also of these types. This kind of a flora, which might perhaps be termed unrepresentative, renders exact correlations difficult and makes satisfactory comparisons possible only with such floras as those preserved in the typically marine beds of the Black Creek formation of the Carolinas or with the upper Tuscaloosa and Eutaw floras of Alabama. In the absence of later records in this area it is impossible to surmise, for example, how many of the elements found in the lower Tuscaloosa of Alabama survived as late as the Cusseta sand member of the Ripley formation and how many had become extinct. The uniformity of the Eastern Cretaceous floras from the Magothy of New Jersey to the Tuscaloosa of Alabama, over a distance of 900 miles or more in a northeast-southwest direction, indicates strongly that many of these types were present in the Georgia flora, for the small representation of plants found in the overlying middle division of the Ripley formation is entirely different in character. This condition is similar to that exhibited by the differences of certain western interior floras, such as those of the Colorado and Montana groups.

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[1] Lesquereux, Leo, Mon. U. S. Geol. Survey, vol. 17, 1892, p. 116, Pl. XXXVIII, fig. 7.

[2] Hollick, Arthur, Mon. U. S. Geol. Survey, vol. 50, 1906, p. 102, Pl. XXXIX, fig. 7.

As previously mentioned, the Georgia Cretaceous flora numbers 32 species, distributed among 16 families in 14 orders. A single fern, a species of Dryopterites of the family Polypodiaceæ, is recorded from one locality. Its modern representatives are so varied, numerous, and widespread that it furnishes no satisfactory data for climatic or other physical speculations. The conifers are represented by 7 species, the majority apparently belonging to the subfamily Araucarieæ, although the relatively primitive Taxaceæ are represented by a species of Tumion. The Monocotyledonæ are represented by two forms of little significance, although one appears to be most closely allied with certain modern tropical forms. The Dicotyledonæ number 22, and include in addition to the remarkable genus Manihotites a scattering of forms. There are four species of Ficus, three of which have coriaceous lanceolate leaves, and three species of willow, probably, like the modern willows, mesophytic river-bank types. There are three species of Andromeda which doubtless owe their preservation to their small coriaceous leaves, and two species each of Magnolia and Cinnamomum. The genera Juglans, Menispermites, Paliurus, Zizyphus, Malapoenna, Aralia, and Eucalyptus are each represented by a single species, those species belonging to Menispermites, Paliurus, and Zizyphus being new to science.

As the botanical facies shown by this flora is due largely to the resistant character of the foliage preserved, combined with what are usually termed the accidents of preservation, little is to be gained by any comment on the relative abundance of some types or the absence of others.

PHYSICAL CONDITIONS INDICATED BY THE FLORA.

The physical conditions that bore upon the Upper Cretaceous flora of Georgia were probably substantially the same as those already described as existing in South Carolina. (See pp. 67–68.)

The climate was probably mild and without frost, the humidity was high, and the rainfall was abundant and probably distributed somewhat uniformly throughout the year.

RANGE OF THE MESOZOIC FLORA.

To illustrate some of the features of Mesozoic plant distribution and the relative and apparently progressive restriction in range which has taken place in comparatively recent times, the writer has introduced the accompanying sketch maps (figs. 4–8), which show in a generalized way the range in the existing flora of the genera Cinnamomum, Eucalyptus, Araucaria, and Tumion. When the known occurrences of these genera during the Cretaceous are plotted on maps of the world several very important and interesting features are brought out, and additional data derived from other forms, such as the Magnoliaceæ, Proteaceæ, and Actinostrobeæ are entirely in accord with the conclusions reached in this way.

In a general way there has been a restriction of a number of these Mesozoic types or their descendants to the Southern Hemisphere, where they have become isolated in one or in both of the continental land masses which project southward from the almost circumpolar land mass of the Northern Hemisphere. That this restriction is more in the nature of a segregation by the extinction of intermediate links in the chain of distribution rather than an actual migration away from hostile or toward optimum conditions for growth and reproduction is well shown by the cosmopolitanism of most fossil floras, particularly those of the Mesozoic. The present distribution of Tumion, Taxodium, Sequoia, Sassafras, and Liriodendron is corroborative of this generalization, for the isolation, by extinction, of these genera and of many others that might be mentioned, has left their modern representatives in favorable areas, not in the

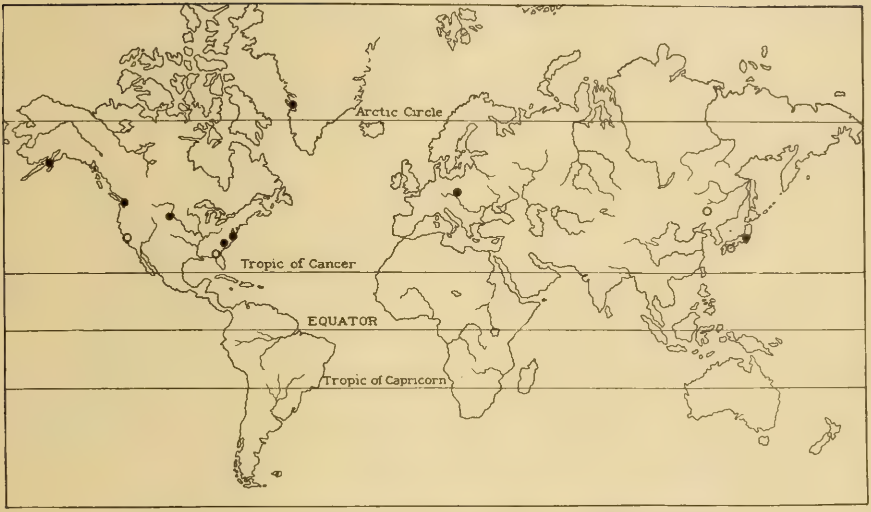

FIGURE 4.—Sketch map showing the Cretaceous (●) and Recent (O) distribution of Tumion.

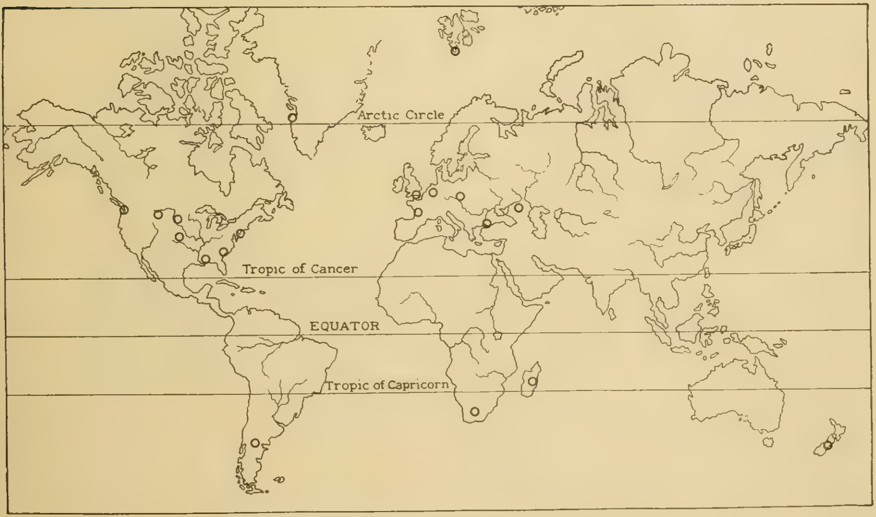

FIGURE 5.—Sketch map showing the Cretaceous occurrences of the Araucarieæ.

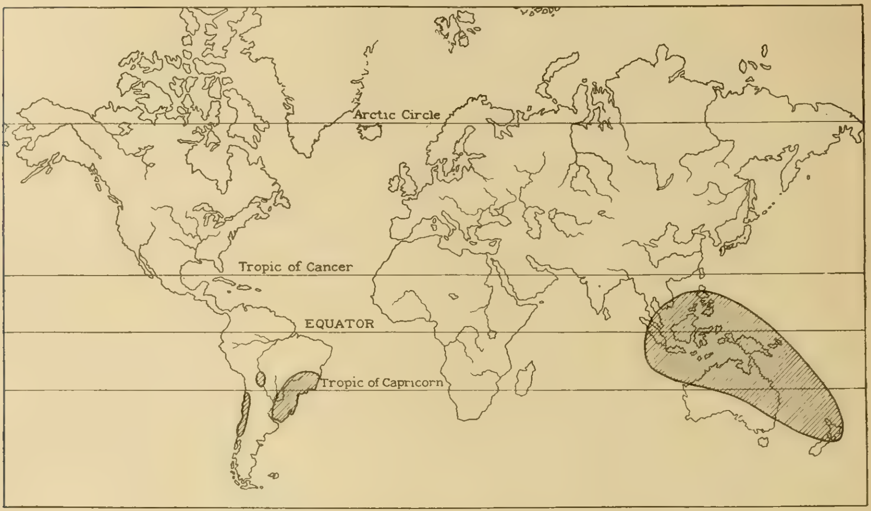

FIGURE 6.—Sketch map showing the existing distribution of the Araucarieæ.

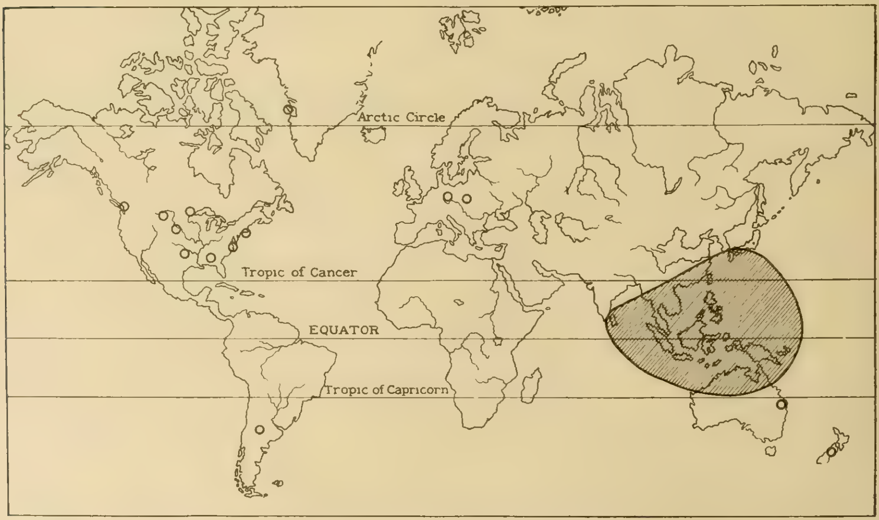

FIGURE 7.—Sketch map showing the Cretaceous (O) and Recent (shaded) distribution of Cinnamomum. The Recent limits should have been extended to include India.

southern continents, but north of the equator. Tumion, for example, has one species at a single locality in Florida, another in California, and two or three others in China and Japan. The once cosmopolitan Taxodium has a single eastern American species at the present day and a climatically stranded form in Mexico. Sequoia, once of world-wide distribution has the two well-known species of the Pacific Coast States. Sassafras is now reduced to a single eastern American species, and Liriodendron to a single American species and another in eastern Asia, though both these genera as well as Taxodium continued to be prominent elements of the cosmopolitan flora as late at the Pliocene.

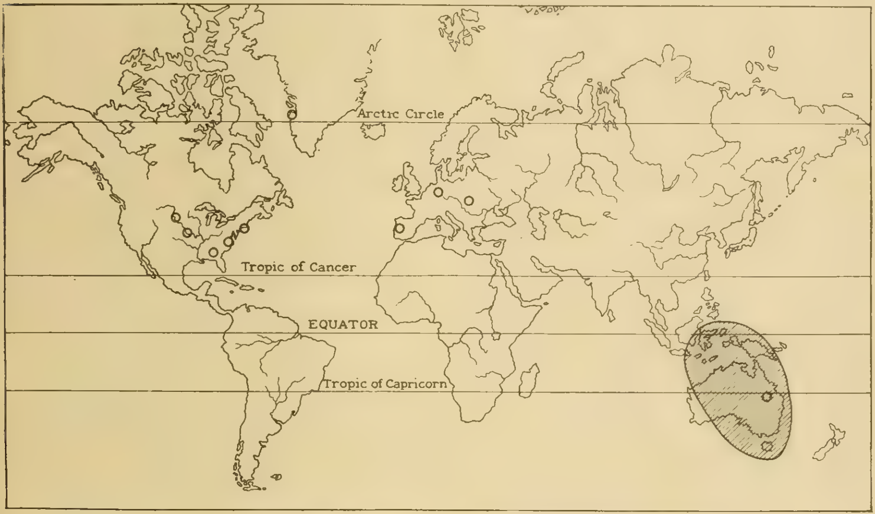

FIGURE 8.—Sketch map showing the Cretaceous (O) and Recent (shaded) distribution of Eucalyptus.

CORRELATION OF THE FLORA.

LOWER DIVISION OF THE EUTAW FORMATION.

The fossil plants from the lower division of the Eutaw formation represent the following 27 species:

Andromeda cretacea Lesquereux ?
Andromeda wardiana Lesquereux.
Androvettia elegans Berry.
Aralia eutawensis Berry.
Araucaria bladenensis Berry.
Araucaria jeffreyi Berry.
Brachyphyllum macrocarpum formosum Berry.
Cinnamomum heerii Lesquereux ?
Cinnamomum newberryi Berry.
Eucalyptus angusta Velenovsky.
Ficus crassipes Heer.
Ficus krausiana Heer.
Ficus ovatifolia Berry.
Juglans arctica Heer ?
Magnolia boulayana Lesquereux.
Magnolia capellinii Heer.
Malapoenna horrellensis Berry.
Manihotites georgiana Berry.
Menispermites variabilis Berry.
Paliurus upatoiensis Berry.
Phragmites pratti Berry.
Salix eutawensis Berry.
Salix flexuosa Newberry.
Salix lesquereuxi Berry.
Sequoia reichenbachi (Geinitz) Heer.
Tumion carolinianum Berry ?
Zizyphus laurifolius Berry.

These species are very unequally represented at the three localities within the Eutaw formation where fossil plants have been found, 19 coming from McBrides Ford, near the base of the formation, though only 5 were collected from Broken Arrow Bend, also near the base of the formation, and 7 from Chimney Bluff, near the top of the formation. The only species present at more than one locality are *Salix flexuosa* and *Sequoia reichenbachi*, which are present at all three. It is believed, however, that these features are due almost entirely to accidents of preservation, as 20 of the 27 species occur at earlier horizons either in Alabama or along the Atlantic Coastal Plain and 8 occur at later horizons in Georgia or elsewhere. Of these 27 species the new species of Aralia, Menispermites, Paliurus, and Zizyphus are confined to the Eutaw of Georgia and hence are of little value in correlation. Nevertheless they furnish some evidence of value, for the Aralia is closely allied to a species of the Magothy formation, and although Menispermites is represented by a single species, and Paliurus and Zizyphus are not present in any of the floras of the Montana group, all three are common in earlier floras, both in the Coastal Plain and in the Dakota sandstone of the West. Nine species occur in strata as old as the Raritan, 14 are found in the Magothy formation of the northern Coastal Plain, 7 occur in the Middendorf member of the Black Creek formation of South Carolina, 19 are found in the typical Black Creek deposits of North and South Carolina, and 11 have been recognized in the Tuscaloosa formation of Alabama.

Comparisons with floras more remote geographically indicate that 14 of the Georgia species are found in the flora of the Dakota sandstone, whereas only 2 occur in the flora of the Montana group, one of these two species being *Sequoia reichenbachi*, a form which possesses little or no stratigraphic value because it occurs from the base to the summit of the Cretaceous. Five species are common to the Atane beds of Greenland and three to the Patoot beds of the same area, one of these three also being *Sequoia reichenbachi*. Five species are common to the Cenomanian and three to the Turonian of Europe, but the only ones common to the Senonian of Europe are *Cunninghamites elegans* and *Sequoia reichenbachi*.

The preceding statements render any extended discussion superfluous. It is clear that the flora of the Eutaw formation of Georgia is of approximately the same age as the Magothy-Matawan flora of the northern Coastal Plain and the Black Creek flora of the Carolinas. It has much in common with the more extensive Tuscaloosa flora of western Alabama, but is probably younger than the bulk of the Tuscaloosa flora or that found in the Middendorf arkose member of the Black Creek formation.

RIPLEY FORMATION.

CUSSETA SAND MEMBER.

The Cusseta sand has furnished fossil plants at only two localities—one near Buena Vista, in Marion County, and the other near Byron, in Houston County. These plants are few in number and are poorly preserved.

The following species, six in all, have been recognized from the locality near Buena Vista:

Andromeda novæcæsareæ Hollick.
Araucaria bladenensis Berry.
Doryanthites cretacea Berry.
Eucalyptus angusta Velenovsky.
Ficus georgiana Berry.
Manihotites georgiana Berry.

Three of the foregoing species occur in the underlying Eutaw formation, and all but the Ficus, which is new, are found in the Black Creek formation of North and South Carolina. The Andromeda is a characteristic species of the Black Creek formation and is one of the type fossils of the Magothy formation of the northern Coastal Plain, although it makes its earliest appearance in the Raritan formation, as does also the Eucalyptus. None of the six genera except Ficus are represented in the flora of the Montana group, and the latter is represented by very different species. It seems clear, then, that the Cusseta sand is pre-Montana in age and that it falls within the same general paleobotanic limits that include the Magothy-Matawan, typical Black Creek, Middendorf, and upper Tuscaloosa floras of the East and the flora of a part of the Dakota sandstone of the West.

The deposits near Byron seem to lack for the most part any physical or faunal data for accurate correlation; in fact, these extensive interbedded sands and clays constitute landward Cretaceous deposits which may represent the whole of the Upper Cretaceous section along Chattahoochee River or in western Alabama, so that the following comments must be understood to apply only to the horizon yielding the fossil plants, which, according to Stephenson, is referred to the Cusseta member. These plants number but three species—*Dryopterites stephensoni* Berry, *Cunninghamites elegans* (Corda) Endlicher, and *Araucaria jeffreyi* Berry, the first-named form being new to science.

As Dryopterites occurs in the Lower Cretaceous, Dryopteris-like forms are found in post-Cretaceous floras down to the present time, and Dryopteris (Aspidium) is to-day a widespread and dominant genus of ferns, the Georgia species, which is unlike any of the described forms, is of no value in correlation. Of the other two forms, *Cunninghamites elegans* has a rather wide geographic range, occurring both in this country and abroad, and its geologic range is also considerable. In Europe it ranges from the Cenomanian to the Senonian, inclusive, and in this country it has a parallel range, from the Magothy flora of the East to the Montana flora of the West. It has been recorded from Lower Cretaceous horizons in Europe, but these determinations are believed to be erroneous. The nearest geographic occurrence to that in Georgia is that of the upper part of the Black Creek formation of North Carolina; hence the conclusion that the exposures near Byron are not older than those of the Black Creek and not younger than those of the Montana group appears to be firmly established.

The remaining species, *Araucaria jeffreyi*, is not a widespread form, and its intimate association with *Araucaria bladenensis* in the Eutaw formation at Chimney Bluff, Ga., and in the Black Creek formation of North Carolina indicates that it may represent cone scales of the latter species. Taken alone, *Araucaria jeffreyi* points to the same conclusion regarding the age of the deposits near Byron as does the distribution of *Araucaria bladenensis*, but the latter furnishes more definite data.

Araucaria bladenensis is one of the most abundant and typical forms of the Black Creek formation in North and South Carolina, ranging from its base to its summit. It has also been found in the Cusseta sand member of the Ripley formation near Buena Vista, in the Eutaw formation just below the Tombigbee sand member at Chimney Bluff, and in the base of the Eutaw formation in western Alabama. A closely allied or identical form occurs in the Magothy of Maryland and New Jersey, and a similarly allied form has been described from the Turonian of France and Bohemia. Though the lower limit of the species is settled, therefore, with some degree of certainty, its upper limit remains vague. It is not found above the horizon represented by the plant beds near Buena Vista, which are placed in the Cusseta sand. This fact is not so important, however, as it would at first appear, for the floras from the later Cretaceous in the eastern United States are extremely meager. However, as nothing in any way allied to it has been discovered in the abundant floras of Montana or later Cretaceous age in the West, the evidence points to its pre-Montana age.

Nothing has been said in the foregoing pages of the probable European equivalents of these floras—a most fascinating as well as a most difficult problem. It is well not to be dogmatic until the associated faunas are critically studied, and even then a close parallelism between areas as remote as the opposite shores of the Atlantic is hardly to be expected. Nevertheless, the sequence of events in both the Lower and the Upper Cretaceous furnishes certain broad similarities, and some correlations, though they are necessarily approximate, appear to be justified.

In the European Upper Cretaceous section Cenomanian floras appear in Portugal, France, Germany, Bohemia, Dalmatia, and elsewhere. The Turonian has few fossil plants, the largest floras being those of Bohemia and southern France, which have perhaps a score of species. The Emscherian furnishes a more representative flora, principally from Germany, Bohemia, the Tyrol, and other scattered localities in Austria. As regards the classic American Upper Cretaceous section of Meek and Hayden, it has been customary to correlate the Dakota sandstone with the Cenomanian, the Colorado group with the Turonian, and the Montana group with the Senonian. In a study of the northern Coastal Plain the writer has found good grounds for considering the Raritan formation to represent part of the Cenomanian.[1] The Magothy has also been referred at various times to this epoch, the Matawan to the Turonian, and the Monmouth to the Senonian. More recently Weller has suggested that the Magothy and the Matawan are also to be correlated with the Senonian. The writer does not purpose to discuss the faunal evidence in this connection, for others are better qualified to do that work. It becomes, however, a paleobotanic question, for in the Black Creek formation of North Carolina the Matawan fauna is found associated with the Magothy flora, as indeed it is to a considerable extent in the Magothy formation in the New Jersey area. In a recent discussion of the correlation of the Black Creek formation of North Carolina, Clark[1] has correlated it with the combined Magothy and Matawan formations of New Jersey and has suggested that it may represent the European Turonian, the lower limit of the Senonian equivalents in the eastern United States being marked by the introduction of the *Belemnitella americana* fauna.

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[1] Berry, E. W., Jour. Geology, vol. 18, 1910, pp. 252-258.

. The floral evidence is entirely favorable to this interpretation, which would involve consideration of the Dakota sandstone and the overlying Benton as of Turonian age. There can be no question in the mind of anyone competent to judge the evidence that these eastern floras from Georgia northward are closely allied to the Dakota flora and markedly distinct from any described floras of the Montana group. The accompanying table of distribution shows the occurrences of fossil plants in Georgia and their range elsewhere, and furnishes a graphic summary of the preceding discussion.

Distribution of Upper Cretaceous plants in Georgia and their range elsewhere.

	Georgia localities.					Raritan formation, New Jersey to Maryland.	Magothy formation, New Jersey to Maryland.	Black Creek formation, North and South Carolina.	Tuscaloosa formation, Alabama.	Woodbine sand, Texas.	Dakota sandstone, western interior.	Montana group, western interior.	Atane beds, Greenland.	Patoot beds, Greenland.	Cenomanian, Europe.	Turonian, Europe.	Senonian, Europe.
	McBrides Ford.	Broken Arrow Bend.	Chimney Bluff.	Near Buena Vista.	Near Byron.												
Dryopterites stephensoni					×												
Androvettia elegans	×																
Araucaria bladenensis			×	×			×	×								?	
Araucaria jeffreyi			×		×			×								?	
Brachyphyllum macrocarpum formosum	×						×		×	×		×					
Cunninghamites elegans					×		×	×				×		×	×	×	×
Sequoia reichenbachi	×	×	×			×	×	×	×		×	×	×	×	×	×	×
Tumion carolinianum (?)	×							×									
Phragmites pratti		×						×									
Doryanthites cretacea				×			×	×									
Juglans arctica (?)	×					×	×	×			×		×				
Salix flexuosa	×	×	×			×	×	×	×		×						
Salix lesquereuxii			×			×	×	×			×						
Salix eutawensis		×						×									
Ficus krausiana			×				×	×	×		×				×	×	
Ficus crassipes			×				×	×	×		×		×				
Ficus georgiana				×													
Ficus ovatifolia	×					×	×	×	×								
Magnolia boulayana	×					×	×		×	×	×						
Magnolia capellinii	×						×	×	×		×		×		×		
Menispermites variabilis	×																
Manihotites georgiana	×			×				×									
Paliurus upatoiensis	×																
Zizyphus laurifolius	×																
Cinnamomum newberryi	×					×	×	×	×	×	×		×	×	?		
Cinnamomum heerii (?)	×						×	×	×	×	×						
Malapoenna horrellensis		×						×									
Aralia eutawensis	×																
Eucalyptus angusta	×			×		×		×							×		
Andromeda novæcæsareæ				×		×	×	×	×	×							
Andromeda cretacea (?)	×										×						
Andromeda wardiana	×								×		×						

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[1] Clark, W. B., Bull. Geol. Soc. America, vol. 20 (1908), 1910, pp. 653, 654.

THE MIDDLE EOCENE FLORA OF GEORGIA.

INTRODUCTION.

This paper gives a preliminary account of a small flora collected from the middle Eocene of Georgia. This flora, though containing only a few species, is of exceptional interest in the biologic problems which it suggests and is likely to prove of considerable geologic value in the study of the Gulf Eocene, the fossil plants of which are to a large extent unknown to science. No fossil plants have previously been described from any of the formations of the Coastal Plain in the State of Georgia, although plant remains are present in both the Cretaceous and the Tertiary rocks. The only published records of Tertiary plants from this area known to the writer refer to two of the localities described in the following pages.

From the Fiske property McCallie,[1] on the authority of F. H. Knowlton, recently enumerated: "A palm near to the living *Sabal adansoni*, Castanea resembling *Castanea dentata*, Quercus sp ?, Ficus sp. ?"

From the locality south of Macon on the Macon-Marion public road, the same author[2] mentions "several species of fossil leaves." None of these collections, however, has previously received critical study, and in fact no definite floral remains have ever been recorded from deposits of Claiborne age anywhere throughout the territory in which it outcrops. Fossil plants are said to occur in the Claiborne of Alabama at two localities, but so far as the writer can ascertain no collections have ever been made from either of these. At the classic type locality at Claiborne Landing on Alabama River, near the top of the celebrated "Claiborne sands," there is, according to Smith and Langdon,[3] a lens of laminated gray clay with leaf impressions, and bands of lignite are said also to occur in these same beds. Langdon[4] also records lignitic sandy clays full of fossil leaves on Conecuh River, in southern Alabama.

The upper formation (Yegua or "Cockfield") of the Claiborne group in the southern Arkansas and northern Louisiana area is said by both Harris and Veatch to contain numerous plant-bearing and lignitic beds. It seems certain that when the Claiborne deposits of the Mississippi embayment are studied in greater detail a considerable flora will be discovered.

GEOLOGY OF THE MIDDLE EOCENE.

The Claiborne group of Georgia reaches its greatest exposed development in a belt extending from Savannah River on the northeast to Ocmulgee River on the southwest. Beyond the Ocmulgee it is deeply buried by the transgression of the Vicksburg and Jackson formations and is exposed only along Chattahoochee River south of Fort Gaines[5] and along Flint River, where Veatch and Stephenson have discovered Claiborne fossils at Penny Bluff, west of Americus. This northeastern belt is 10 to 30 miles in width, and is the only area of interest in the present connection, because it contains the only known Eocene plants in the State. The materials consist of heavy beds of sand, in many places indurated and pebble-bearing, extensive lenses of porous laminated clays with some local limestones and marls, and in some places lignitic deposits. In general the clays represent deposition in the early part of Georgia Claiborne time.[6] They are light in color but are in many places iron-stained. They are laminated or thinly bedded with films of fine light sand, and commonly contain impure calcareous nodules and thin layers of soft limestone of small areal extent. These clays are more or less continuous from Augusta southwestward to Twiggs and Bibb counties. Immediately above the clays, and replacing them in some areas, are heavy beds of iron-stained sands, which are in many places salicified and fossiliferous, and which show very commonly toward their upper limits phases of sandy fossiliferous marl, as at Shell Bluff, in Burke County.

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[1] McCallie, S. W., Underground waters of Georgia: Bull. Geol. Survey Georgia No. 15, 1908, p. 336.

[2] Idem, p. 347.

[3] Report on the geology of the Coastal Plain of Alabama, 1894, pp. 126, 129.

[4] Idem, p. 387.

[5] McCallie, S. W., op. cit., p. 33.

[6] The Georgia Claiborne, in the light of later studies of the fossil plants collected in Alabama, Mississippi, and Louisiana, appears to represent the upper Claiborne of the complete Gulf section.

The thickness of the Claiborne group in Georgia is placed between 300 and 500 feet, divided into Barnewell sand above and the McBean formation below. The fossil plants come from the basal part (Congaree clay member) of the McBean formation.

The Claiborne in Georgia generally rests with marked unconformity upon the Cretaceous, locally transgressing those rocks and resting on the eroded surface of the crystalline rocks of the piedmont. It is overlain by the Vicksburg and Jackson formations or by the surficial deposits of the Lafayette? and later formations. Most of the fossil plants enumerated in the following pages were collected in the vicinity of Grovetown, in Columbia County, 15 miles west of Augusta on the Georgia Railroad. The Claiborne deposits in this region occupy a pre-Claiborne estuary deeply eroded in the underlying Cretaceous surface, outcropping as a narrow tongue only 2 or 3 miles in width and extending to the northwest from the main body of the Claiborne deposits in Richmond County a distance of about 18 miles.

The stratigraphic relations are well illustrated by the diagrammatic section (fig. 9) of the plant-bearing horizon in Phinizy Gully. This gully extends in an approximately east-west direction about 1 mile east of the Grovetown railroad station and was formerly used by the Augusta-Wrightsboro wagon road, long since abandoned. The east-west line in the figure marks the bed of the gully. The Eocene clay is laminated with fine sand partings and local layers of comminuted lignite, and contains scattered leaf impressions and casts of Modiolus and small Pelecypoda. Most of the leaf impressions, which are nowhere abundant, carry only sufficient carbonaceous matter to form a very light tan impression, which furnishes beautiful specimens of good lasting qualities, their preservation being endangered only by the usually great shrinkage of the clay in drying.

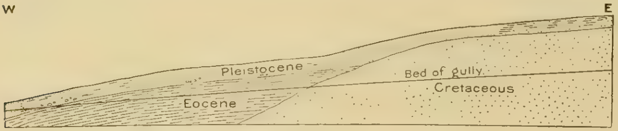

FIGURE 9.—Diagrammatic geologic section of Phinizy Gully.

Eastward up the gully, some 50 or 60 feet beyond the plant locality, appear abruptly the light-colored coarse gravelly arkosic sands of the Lower Cretaceous. These become argillaceous in their upper part and rise 10 to 15 feet above the Eocene surface, and deposits of both ages are overlain in the sides of the gully by a thin covering of Pleistocene and Recent deposits, the whole furnishing an exceptionally fine example in small compass of an erosional unconformity.

The plant locality known as the Fiske property contains several small pits, the principal opening being just east of the Grovetown railroad station along the Georgia Railroad. It was formerly worked and the product marketed as a fuller's earth, but it has been idle for some time. At the time of the writer's visit the sides had slumped a great deal and the pit was full of water. The laminated clay appears again along the railroad in a low cut a short distance north of the station, where it contains unidentifiable fragments of leaves. About 1¼ miles southwest of Grovetown station and one-half mile west of the railroad track recent erosion exposes the laminated clays. At this locality indistinct invertebrate impressions and fragments of Acrostichum, too poor to be worth collecting, were observed. That remains of the vegetation of the Claiborne are not everywhere uncommon is shown at a locality 3½ miles south of Grovetown, known as the Chapman lignite mine. At this locality about 10 feet of black, compact, earthy lignite, filled with trunks and limbs of trees, is exposed beneath pinkish clays and coarse Eocene sands. The base of the lignite is not exposed and its thickness or horizontal extent is unknown. It is by far the largest known lignitic deposit in the State, reminding the observer of the Upper Cretaceous and Eocene lignite beds of the far West or those of the Wilcox group in the Mississippi embayment. Specimens of wood from these deposits were found, when prepared for microscopic examination, to have undergone too much decay before entombment to permit of identification except to the extent that they were dicotyledonous—a fact worthy of comment, for in the recent coal work in the western lignitic areas it has been found that the recognizable lignites are nearly all of coniferous origin, although the enormous number of dicotyledonous leaf impressions in the surrounding clays effectually testify to the abundance of this class of plants during the formation of the lignite beds.

Two other plant localities remain to be mentioned. One is represented by a single specimen obtained in digging a well near Poplar Church, 13½ miles west of Sandersville, in Washington County. The second is on the Macon-Marion public road, 10 miles south of Macon, in Twiggs County, at the old Thorpe place. Here there is an exposure of nearly 100 feet of the "fuller's earth," overlain by 50 feet of red argillaceous sand. The clay is less thinly bedded at this locality, but the thin seams of comminuted leaves are exactly like those seen at Phinizy Gully, and the identifiable leaf remains are scattered irregularly in the same way but are less common.

The Claiborne deposits near Hephzibah, in Richmond County, contain fragments of leaves and numerous impressions of twigs and small stems, but the writer was unable to identify anything at this locality. It was also impossible to identify any of the poorly preserved leaf impressions of a small collection made recently by Otto Veatch, of the Geological Survey of Georgia, on the Fort Gaines-Edison public road, 2½ miles east of Fort Gaines, in Clay County.

The species identified from all the known plant-bearing Claiborne outcrops in Georgia are brought together in the following table:

Distribution of the Claiborne flora in Georgia.

	Fiske property, Grovetown.	Phinizy Gully, near Grovetown.	10 miles south of Macon.	Poplar Church.
Acrostichum georgianum		×		
Arundo pseudogoepperti		×	×	
Castanea claibornensis	×			
Conocarpus eocenica	×	×	(?)	
Dodonæa viscosoides	×	×	×	
Ficus claibornensis	×		×	
Malapoenna sp.			×	
Mimosites georgianus	×	×	×	
Momisia americana		×		
Pisonia claibornensis		×	(?)	
Pistia claibornensis	×			
Potamogeton megaphyllus		×		
Rhizophora eocenica		×	×	×
Sapindus georgiana		×		
Sphærites claibornensis	×		×	
Terminalia phæocarpoides	×			
Thrinax eocenica	×	×		

A considerable fauna is listed from the various outcrops by McCallie,[1] the determinations being by Vaughan and Dall. Invertebrates have been found closely associated with the plant remains at several points. The smaller figured specimen of Thrinax contains several impressions of Modiolus and small pelecypod shells, and one of the best specimens of Acrostichum is partly hidden by a Modiolus valve. The collections from the Fiske property include the following invertebrates:[2]

Turbinella (Psilocochlis) mccalliei Dall.
Calyptrea aperta Solander.
Nucula magnifica Conrad.
Nucula ovula Lea.
Leda, 2 sp.
Ostrea sp.
Modiolus texanus Gabb.
Modiolus alabamiensis Aldrich?
Cytherea ovata var. greggi Harris.
Balanus sp.

From the plant locality on the Macon-Marion public road the following invertebrates are recorded:[3]

Nucula ovula Lea.
Crassatellites protexta Conrad.
Diplodonta sp.

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[1] McCallie, S. W., op. cit., pp. 336-348.

[2] Idem, p. 336 (identified by Vaughan).

[3] Idem, p. 347 (identified by Vaughan).

From the well near Poplar Church which furnished a leaf of *Rhizophora eocenica* the following invertebrates are recorded:[1]

Nucula ovula Lea.
Glycymeris trigonella Conrad.
Ostrea alabamiensis Lea.
Modiolus aff. texanus Gabb.

As already stated, the Claiborne has a very considerable areal extent outside the region considered in this report; in fact it is one of the most extensively developed groups of marine beds in the Coastal Plain and is certainly the most extensive post-Cretaceous group, for it has a known extension from the Rio Grande on the south to the Carolinas and probably to Maryland on the north. Its extremely fossiliferous character early attracted attention, and a study of collections of invertebrate remains from a local development of beds of this age at Claiborne Landing on Alabama River enabled Conrad in 1835 to prove the presence of Eocene beds in the Gulf Coastal Plain. The name Claiborne as at present understood is applied to a larger unit as a group term. Plant remains are present in some of the more argillaceous members at the type locality on Alabama River, but these have never been collected. The comparison of this flora with that of the Georgia Eocene would prove a most interesting and valuable study.

The shore line was not stationary during Claiborne time, for considerable oscillation is indicated in the change from marine to estuarine sedimentation in the Mississippi embayment region. The Eocene Gulf Stream was no doubt a large factor in the northward extension of the southern flora which occurs at Grovetown. With the recession of the sea as Eocene time progressed and the emergence of the Florida area in the Miocene, this warm current would be deflected somewhat to the east. Considerable evidence has been set forth by Dall, and more recently by Vaughan, for the existence of a cooler inshore current in the middle Miocene.

With regard to the existence of land to the southward little is known. The vertebrate paleontologists, notably Osborn, insist on a late Cretaceous or early Eocene land connection with South America to account for the mammalian fauna of the Notostylops beds of Patagonia and the presence of Edentata-Dasypoda in the North American middle Eocene. Corroborative evidence is furnished by the appearance of the flora of the Dakota sandstone in Argentina, although this land connection is vigorously denied by other students.

In any event, the Georgia Eocene flora need not be supposed to have migrated from equatorial South America. It undoubtedly flourished during the whole of the Tertiary all along the then-existing coast from the Mexico-Central America region to the Georgia occurrence.

SYSTEMATIC DESCRIPTION OF THE FLORA.

Phylum THALLOPHYTA.

Order PYRENOMYCETES.

Genus SPHÆRITES Unger.

SPHÆRITES CLAIBORNENSIS sp. nov.

Plate XXIV, figure 6.

Description.—Perithecia small and numerous, arranged in elevated rings 1 to 1.5 millimeters in diameter on the upper surface of the leaves of Ficus.

Large numbers of fungi of this sort have been described by European paleobotanists, chiefly from Tertiary horizons, and referred to the genera *Sphæria* Haller or *Sphærites* Unger. They possess little biologic interest except in so far as they indicate the presence of this class of plants in various bygone floras, and American paleobotanists have usually ignored them entirely.

The present species is similar to *Sphærites myricæ* (Lesquereux) Meschinelli,[2] from the Green River formation of Wyoming, a form which occurs on leaves of a species of Myrica, and to *Sphærites nervisequus* Fritel,[1] from the Sparnacian of the Paris Basin, a type, somewhat smaller than the Georgia form, which occurs on the leaves of a species of Lauraceæ.

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[1] McCallie, S. W., op. cit., p. 343 (identified by Vaughan).

[2] Lesquereux, Leo, The Tertiary flora, 1878, p. 34, Pl. I, fig. 4.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Fiske property, Grovetown, Columbia County, 10 miles south of Macon, Twiggs County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Phylum PTERIDOPHYTA.

Order FILICALES.

Family POLYPODIACEÆ.

Genus ACROSTICHUM Linné.

ACROSTICHUM GEORGIANUM sp. nov.

Plate XXVII, figure 1.

Description.—Frond large, pinnate (?). Pinnæ thin but coriaceous, oblong-lanceolate, inequilateral, with an entire undulating margin, an obtusely rounded apex, and a narrowed (?) base, about 2.5 centimeters in width and of unknown length, presumably about 10 to 12 centimeters. The pinnæ may have been considerably larger than is here indicated, for all the collected material is fragmentary and in some of the fragments the thin stiff edges are folded over, indicating a possible greater width. Midveins stout. Lateral veins numerous, 1 millimeter or less apart, very fine intricately anastomosing, branching from the midvein at acute angles, the angle dependent on their situation in the basal or apical part of the pinna. The basal veins subtend angles of about 60°; those in the apex approach a position almost parallel with the midvein; and the intermediate ones branch at a very acute angle and immediately diverge outward, their general direction being about 50° from that of the midvein. Areolation of slightly elongated, 5 or 6 sided meshes.

What appear to be fragments of the fertile pinnæ of this species occur at the locality 10 miles south of Macon, but they are too uncertain to be even tentatively identified as such and are not included among the occurrences of this species listed herewith. Nevertheless the fragments are so suggestive of this species that, if sterile pinnæ had been found at the same locality, the writer would not hesitate to class them as fragments of fertile pinnæ.

This handsome species is unfortunately based on fragments, the largest being that figured. There are eight such specimens from the Phinizy Gully locality, one partly concealed by a valve of Modiolus. Still smaller fragments showing the characteristic areolation were noticed at other outcrops in the vicinity of Grovetown.

The species is closely related to *Acrostichum hesperium* Newberry,[2] of the Green River formation of Wyoming, differing from it in being somewhat more slender in habit and in having straighter midveins and less elongate, finer areolation. There is no evidence of the coalescence of the terminal pinnæ, a feature which serves to distinguish Newberry's species from all other described fossil species of Acrostichum.

A similar form is the European *Acrostichum* (*Chrysodium*) *lanzæanum* Gardner and Ettingshausen,[3] described at length by Gardner and common in the Lutetian and Bartonian of southern England. What appear to be identical remains are reported from the Ligurian of Dalmatia and southern Franch, from the Tongrian of France and Italy, and more doubtfully from the Ypresian of France. Another species is reported by Saporta from the Aquitanian of southern France, and Squinabol reports two additional species from the Tongrian of Liguria, Italy.

Another American species of Upper Cretaceous or lower Eocene age was described in 1902 by Hollick[4] from Colorado. In this connection mention should also be made of a fern from

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[1] Fritel, P. H., Mém. Soc. géol. France, vol. 40, 1910, p. 13, Pl. I, fig. 14.

[2] Newberry, J. S., The later extinct floras of North America: Mon. U. S. Geol. Survey, vol. 35, 1898, p. 6, Pl. LXI, figs. 2–5.

[3] British Eocene flora, pt. 1, 1879, p. 26, Pls. I and II, figs. 1–4.

[4] Torreya, vol. 2, 1902, p. 146, Pl. IV, figs. 3–6.

Sand Creek, Colo., described by Lesquereux[1] as *Gymnogramma gardneri,* which both Gardner and Saporta are inclined to consider an Acrostichum. This fern is of Upper Cretaceous or basal Eocene age.

The modern species of Acrostichum are swamp forms. They are few in number and include, in addition to several unimportant species of the Lesser Antilles and West Indies, the widespread tropical fern, *Acrostichum* (*Chrysodium*) *aureum* Linné, a common coastal species of mangrove and nipa swamps and similar situations, more particularly on the dryer and less saline soils, which ranges in America from Bermuda and peninsular Florida to Brazil, in Africa from Guinea to Natal and the Mascarene and Seychelles islands, and in the Orient from southern China and Polynesia to northern Australia. It is remarkable that this cosmopolitan modern genus should appear about the same time in America and Europe and display a number of closely allied forms at widespread localities in both the Eocene and Oligocene, and yet not be detected at any of the numerous outcrops of later Miocene or Pliocene plant-bearing deposits. Undoubtedly this southward retreat from latitude 51° north is to be explained by changing physical conditions, chief among which were lessening humidity and lowering temperature.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Phinizy Gully, Columbia County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Phylum SPERMATOPHYTA.

Class ANGIOSPERMÆ.

Subclass MONOCOTYLEDONÆ.

Order POALES.

Family POACEÆ.

Genus ARUNDO Linné.

ARUNDO PSEUDOGOEPPERTI sp. nov.

Plate XXIV, figure 7.

Arundo goepperti? Münster, in Lesquereux, Ann. Rept. U. S. Geol. and Geog. Survey, Terr., 1871, suppl., p. 5.
Arundo goepperti? Münster, in Lesquereux, The Tertiary flora, 1878, p. 86, Pl. VIII, figs. 3–5.

Description.—Lesquereux in 1871 and again in 1878 referred several fragments of leaves and striated stems of grasslike form found in the Green River formation to the well-known European species *Arundo goepperti.* These fragments agree fairly well with the European material, but when it is considered that remains of this kind have little to distinguish them specifically, and that these American forms are so far removed geographically from the type forms and occur at a horizon invariably of considerably greater age, the propriety of considering them distinct is obvious.

A number of fragments from Phinizy Gully are referred to this species, one of the best, although not the largest, being figured. The most that can be said of their botanic relationship is that they represent large marsh grasses analogous, if not intimately related, to the modern genus Arundo, to which they are referred as a matter of convenience and long standing usage rather than because of any very definite proof of this relationship.

In his elaboration of the Green River flora Lesquereux has described an additional but similar species, *Arundo reperta,*[2] and other remains which he refers to Phragmites. It is quite possible that some of these remains, especially those named *Arundo reperta,* are referable to the present species.

The modern species of Arundo, which number about six, are distributed throughout the warmer countries of the world. This species and the original *Arundo goepperti* are usually compared with the modern *Arundo donax* Linné, which is indigenous to the Mediterranean region and which grows in wet places.

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[1] The Tertiary flora, 1878, p. 58, Pl. IV, fig. 2.

[2] The Tertiary flora, 1878, p. 87, Pl. VIII, figs. 6–8.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Phinizy Gully, Columbia County, 10 miles south of Macon, Twiggs County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Order NAIADALES.

Family NAIADACEÆ.

Genus POTAMOGETON Linné.

POTAMOGETON MEGAPHYLLUS sp. nov.

Plate XXVII, figure 2.

Description.—Leaf ovate-lanceolate in outline, 8 or 9 centimeters in length by 3.6 centimeters in greatest width, which is in the basal half of the leaf. Apex not seen, but the margins converge abruptly apically, so that it was rather obtusely or acutely pointed. Base rounded. Veins numerous, about 1 millimeter apart, unbranched, acrodrome. Midrib not differentiated. Transverse veinlets not visible. Texture apparently thin and firm.

The present species resembles a number of fossil forms of undetermined botanic affinity such as *Smilacina rackiana* Pilar,[1] of the later Tertiary of Europe. It comes closest, however, to the leaves from Trocadéro in the Eocene of the Paris basin (Lutetian), referred by Saporta[2] to the genus Ottelia Pers (Hydrocharitaceæ), but described originally as a species of Potamogeton by both Brongniart[3] and Watelet[4] and referred by Bureau to the genus Monochoria of the Pontederiaceæ.

Between 30 and 40 fossil species have been referred to this genus, none of which appear to be identical with the Georgia form. They range in age from the Arctic Senonian through the Eocene, Oligocene, Miocene, and Pliocene to the Pleistocene, several still existing species being recorded from the latter, both in this country and abroad.

The modern species number more than 60 and occur both in the tropics and in the temperate zone, with a larger representation in the latter. The species generally have a wide, many a cosmopolitan range, a single species commonly extending over a great many degrees of latitude; for example, *Potamogeton perfoliatus* Linné extends over more than 20 degrees of latitude in America, from Newfoundland and British Columbia to Florida and California, and also occurs in Europe and Asia. It is an interesting fact that all the wide-ranging species extend into both comparatively high and low latitudes, whereas species of more restricted range, such as *Potamogeton floridanus* Small and *Potamogeton curtissii* Morong, of Florida, are commonly confined to warmer regions.

This condition may be taken to indicate either that species confined to low latitudes in the existing flora, or their immediate ancestors in more ancient floras, had originally a much wider range than now, or that the modern wide-ranging species have greatly extended their range in recent times. The writer inclines to accept the latter supposition, although it is well known that the majority of aquatics, both animal and plant, are little influenced even by rather wide differences in latitude.

A fossil species of about the same size as the Claiborne species but with a more open venation has been described by Heer from the Tertiary of Spitzenbergen as *Potamogeton nordenskioldi*.[5] Both this form and the Georgia species probably represent floating, not emerged or submerged, leaves.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Phinizy Gully, Columbia County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

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[1] Pilar, A. G., Flora fossilis susedana, 1883, p. 13, Pl. III, fig. 8.

[2] Le monde des plantes, 1879, p. 227, f. 45.

[3] Tableau, 1849, p. 115.

[4] Description des plantes fossiles du bassin de Paris, 1866, p. 86, Pl. XXIII, fig. 1.

[5] Flora fossilis arctica, vol. 1, 1868, p. 157, Pl. XXX, figs. 1b, 5c, 5d, and 6–8.

Order ARECALES.

Family ARECACEÆ (PALMÆ).

Genus THRINAX Linné.

THRINAX EOCENICA sp. nov.

Plates XXV and XXVI, figure 3.

Description.—Leaves orbicular in outline, of relatively small or medium size, indicating in the collected material a diameter ranging from 36 to 60 centimeters or more. Many-cleft, the numerous rays carinate, much crowded at the obtusely rounded end of the rachis, two cleft distad. Rachis considerably flattened, smooth, entirely unarmed, 1 centimeter wide in the single preserved specimen of one of the smaller leaves. Ligule free, erect, concave, inconspicuous. Segments 25 in number on a small complete specimen; larger fragments showing about two-thirds of a leaf contain 31 rays, indicating that the complete leaf was made up of about 45 segments. The basal rays on each side are somewhat reduced in size and entirely free, and all the rays become separated about two-thirds of the distance from their base. Primary veins prominent. Intermediate veins very fine, five on each side, something less than a millimeter apart, with very fine veinlets between them. (See fig. 10.)

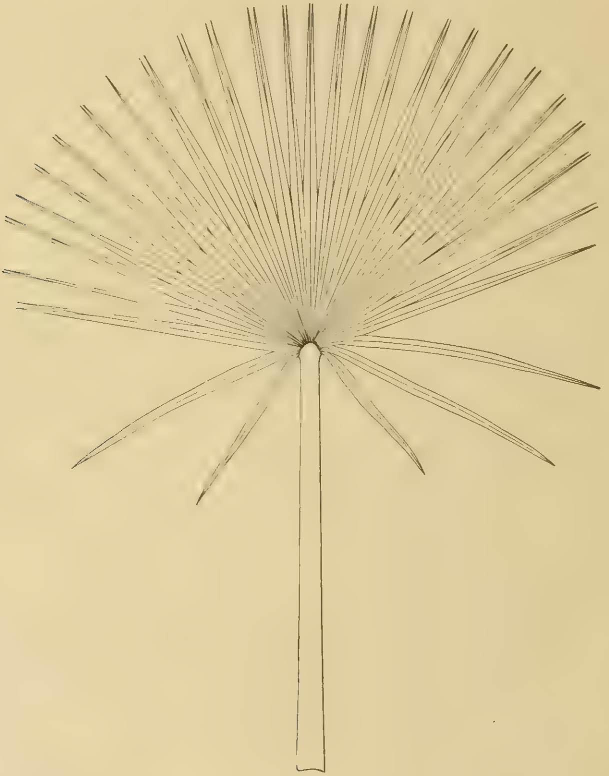

FIGURE 10.—Restoration of *Thrinax eocenica* Berry. (About one-sixteenth natural size.)

Fossil palm leaves present few characters for successful comparison with existing genera; hence the numerous fossil species of such genera as Flabellaria, Sabalites, and Geonomites. The Georgia material is for the most part fragmentary; the greater the size of leaves that floated into the Claiborne sea the more fragmentary the preserved material. These fragments are very common at the Phinizy Gully locality. The two figured specimens, by far the best obtained, are from the Fiske property at Grovetown. The larger is an impression; the smaller, a most beautiful specimen, has the leaf substance preserved and shows the upper surface of the frond. This locality was flooded at the time of the writer's visit and the workings abandoned, but laborers reported that palm leaves were frequently encountered and that some of them reached a diameter of 3 or 4 feet. The present collections, though they leave much to be desired, are in the sum of their characters clearly referable to the genus Thrinax, a determination which the writer made after a careful comparison of the fossil leaves with those of various existing palms in the National Herbarium and in the New York Botanical Garden, and which was immediately suggested by Dr. N. L. Britton when the photographs of these specimens were submitted to him.

The present species is clearly distinct from all the palms described by Lesquereux or Newberry from the West, and little is to be gained by more detailed comparison. It is equally distinct from the homotaxial European palm material, the only material which suggests any relationship being the leaves from the Ligurian of Dalmatia referred by Ettingshausen[1] to *Flabellaria raphifolia* (Sternberg) Ettingshausen. It differs, according to the illustrations given by this author of the same species in his Häring flora, in having a long acumen.

In the modern flora Thrinax has nine or ten species in the West Indies and Antilles, three of the species being found on the Florida Keys.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Fiske property, Grovetown, Columbia County (collected by S. W. McCallie); Phinizy Gully (collected by E. W. Berry).

Collection.—U. S. National Museum.

Order ARALES.

Family ARACEÆ.

Genus PISTIA Linné.

PISTIA CLAIBORNENSIS sp. nov.

Plate XXVI, figures 1 and 2.

Description.—Leaves broadly obovate with a retuse apex giving them an obcordate outline; 2.5 centimeters in length by 2.5 centimeters in greatest breadth. Base broadly cuneate, descending to the wide petiole. Apex with a shallow, broadly rounded sinus. Venation indistinct, fasciculate, forming irregular polygonal meshes by repeated cross branching. There are indications in the fossil of intumescence and inflation in the basal half of the leaf exactly comparable to conditions found in the existing species.

This species is the first to be discovered in the Tertiary, and only three Cretaceous species are known. It is clearly distinct from any previously described fossils, but resembles somewhat certain leaves of *Pistia corrugata* Lesquereux from the Montana group, differing from this species in the degree of apical retuseness. It differs in the same respect from the leaves of the existing species seen by the writer, although the older leaves of the latter tend to a truncate form and are often slightly retuse.

In size, outline, and venation this Eocene species is not very different from the modern *Pistia stratiotes* Linné, in which species Engler (Die natürlichen Pflanzenfamilien) has united all the living representatives of the genus. The result of Engler's classification makes this a somewhat variable and widely distributed species, in general confined to the tropical and subtropical zones. In this country it is found from Florida to Texas. It occurs in the West

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[1] Denkschr. K. Akad. Wiss. Wien, Math.-nat. Kl., vol. 8, 1855, p. 12, Pls. III, fig. 4; XIV, fig. 1.

Indies, and southward through Mexico and Central America to Paraguay and Argentina. In Africa it occurs from Natal to Senegambia and Nubia, and also in Madagascar and the Mascarene Islands. In Asia it appears throughout the East Indies and northward to the Philippines.

Few fossil forms have been referred to this genus. Hosius and Von der Marck[1] described in 1880 a form which they called *Pistites loriformis* from the Lower Senonian of Westphalia, but this is probably cycadean, as Schimper suggested.[2] Lesquereux[3] in 1876 named a remarkably well-preserved form from Point of Rocks, Wyo., *Pistia corrugata*, and later fully described and illustrated it,[4] his specimens including leaves of various sizes and rootlets. This fossil comes from beds belonging to the Montana group (Senonian), which are of about the same age as the French beds from which the only other species, *Pistia mazelii*, was known. This specie was mentioned and figured from the lignites of Fuveau (Provence), France, by Saporta and Marion,[5] but has never been adequately described.

Recently the writer showed[6] Heer's *Chondrophyllum nordenskioldi*, described from the Atane beds of Greenland, to be a true Pistia and to be exceedingly abundant in the Black Creek formation of North Carolina, which is of Colorado (Turonian) age.

It is significant as showing the real imperfection of the geologic record, even of the European Tertiary, that this widespread modern type ranged over at least two continents during the Upper Cretaceous and presumably had a still wider range in Cenozoic times, and yet not a single specimen has ever before come to light at any of the thousands of localities where plant beds of the latter age have been exploited.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Fiske property, Grovetown, Columbia County.

Collections.—U. S. National Museum.

Subclass DICOTYLEDONÆ.

Order FAGALES.

Family FAGACEÆ.

Genus CASTANEA Adanson.

CASTANEA CLAIBORNENSIS sp. nov.

Plate XXVIII, figures 1 and 2.

Description.—Leaves oblong-lanceolate in outline, of a thin, firm texture, about 18 or 19 centimeters in length by 4.5 centimeters in greatest width, which is about halfway between the apex and the base. Apex acuminate (?). Base cuneate, acute. Margin coarsely serrate, with sharp ascending teeth becoming less marked proximad, the margin finally entire toward the base of the leaf. Petiole and midrib stout. Secondaries of medium size, numerous, regular, parallel, and alternate, craspedodrome; they branch from the midrib at angles of about 40° and curve slightly upward, terminating in the marginal teeth. The tertiary venation, which consists of numerous close-set and nearly straight transverse veins, constitutes about the only feature in which these leaves differ from those of our modern American chestnut *Castanea dentata* (Marsh) Borkhausen.

The genus Castanea is represented by a fairly large number of fossil species, one doubtful form occurring as early as the Senonian of Europe. In addition the genus Dryophyllum Debey, often considered as in part ancestral to Castanea and forming a link between the latter genus and Quercus, has a number of species in the Upper Cretaceous and "Paleocene."

Species of Castanea are found in the Eocene deposits in Montana, Oregon, Canada, Alaska, Greenland, France, Italy, and England. There are a number of species in the

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[1] Palæontographica, vol. 26, 1880, p. 182, Pl. XXXVIII, figs. 151, 152.

[2] Zittel's Handbuch, 1890, p. 378.

[3] Ann. Rept. U. S. Geol. and Geog. Survey Terr., 1874, p. 299.

[4] Tertiary flora, 1883, p. 103, Pl. LXI, figs, 1, 3-7, and 9-11.

[5] L'évolution du règne végétale, Phanérogames, vol. 2, 1885, p. 37, figs. 114c and 114d.

[6] Berry, E. W., Bull. Torrey Bot. Club, vol. 37, 1910, p. 189, Pl. XXI, figs. 1-15.

European Oligocene and in the Miocene of Japan, Europe, and America, the latter including some from New Jersey on the east coast and from Oregon on the west coast. No less than eight species have been described from the European Pliocene. These are all very similar and are variously combined and segregated by different authors. They at least indicate the abundance of the chestnut in southern Eurasia during preglacial times.

The common modern chestnut of Europe (*Castanea vulgaris*) is recorded from interglacial beds in northern Italy and France and the modern chinquapin (*Castanea pumila*) is recorded from the American Pleistocene in Kentucky and West Virginia.

Starkie Gardner comments on the incongruity of Castanea being a member of the warm temperate or subtropical Eocene flora and expresses the belief that these supposed chestnuts are really referable to the tropical genus Godoya Ruiz and Pavon (Ochnaceæ). After a careful comparison of the various fossil species with the foliage of this modern genus the writer is strongly of the opinion that Gardner's comparison has no actual basis. A review of the possible evidence bearing on the supposed incongruity of Castanea associated with various tropical and subtropical genera indicates that the modern species of chestnut number five, including *Castanea vulgaris* Lamarck of southern Europe, another species in eastern Asia, and three species in America. Of the latter, *Castanea nana* Muhlenberg is found in the sand hills and barrens of Georgia and Florida to Louisiana. *Castanea dentata* (Marsh) Borkhausen is found on rich, noncalcareous soils from Maine and Ontario to Michigan, Tennessee, Georgia, and Alabama. In the latter State it occurs as far south as Tuscaloosa County, where the mean annual temperature is about 63° F., as against 42° for Maine and about the same for Ontario, Canada. The limits are 21° apart, and indicate a very wide actual range of temperature.

We find that the allied genus Castanopsis Spach, which Prantl[1] makes a section of Castanea, although it appears to be a little nearer Quercus than Castanea, has something like 25 species, mostly of southeastern Asia and tropical India, with one western American species which ranges from southwestern Washington to southern California. The closely allied genus Quercus, though primarily a temperate type, has many strictly tropical species. These various considerations effectually dispose of any criticism of the presence of Castanea associated with Thrinax, Acrostichum, Pisonia, and similar forms in the Eocene of Georgia.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Fiske property, Grovetown, Columbia County. (Collected by S. W. McCallie.)

Collection.—U. S. National Museum.

Order URTICALES.

Family ULMACEÆ.

Genus MOMISIA F. G. Dietrich.

MOMISIA AMERICANA sp. nov.

Plate XXVII, figure 13.

Description.—Leaf ovate in outline, 6 to 7 centimeters in length by 2.6 centimeters in greatest width, which is in the lower half of the leaf. Apex not preserved, presumably acute. Base obtusely pointed. Margin entire as far as seen; there is a possibility, however, that it was sparsely toothed apically. Primaries, three from the top of the petiole, the midrib the stoutest, all slender.

This species is unfortunately based on the single incomplete specimen figured. It is much like the leaves ordinarily referred to the genus Cinnamomum, of which three or four European species have been recognized at innumerable horizons from the Eocene to the Pliocene and at a large number of localities both in this country and abroad. Some of these are indisputable cinnamomums, as is attested by well-preserved fruiting specimens; others find their only relation to that genus in the palmately triveined character. The present species, though it may represent a Cinnamomum, has seemed to the writer to be more closely related to the

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[1] Engler, A., and Prantl, K., Die natürlichen Pflanzenfamilien, pt. 3, 1894.

Ulmaceæ, resembling certain South American species of Celtis, such as *Celtis iguanens* (Jacquin) Sargent of Bolivia. It more closely resembles, however, *Momisia aculeata* (Swartz) Klotsch, a widespread species of tropical America and the West Indies which reaches its northern limits in the valley of the Rio Grande and on the Florida keys.

The genus Momisia has not previously been recorded in a fossil state. In the living flora it has upward of a score of species confined to tropical America. Engler[1] reduces it to a subgenus of Celtis, but there is little doubt that it should be accorded generic rank.

Occurrence. Congaree clay member of McBean formation (of Claiborne group). Phinizy Gully, Columbia County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Family **MORACEÆ** or **ARTOCARPACEÆ**.

Genus **FICUS** Linné.

FICUS CLAIBORNENSIS sp. nov.

Plates XXIV, figure 6, and XXVII, figures 3 and 4.

Description.—Leaves oblong-lanceolate in outline, about 12 centimeters in length by 3.5 centimeters in greatest width, which is about halfway between the apex and the base. Apex acute. Base equally acute and somewhat decurrent on the extremely stout petiole, which is about 3 centimeters in length and fully 3 millimeters in diameter; the petiole is notably curved in one specimen. Midrib apparently equally stout below, becoming thinner above; not well seen because all the collected material shows only the upper surface of the leaves. The texture was evidently coriaceous, much like that in the leaves of the commonly cultivated rubber plant, and the venation is made out with difficulty. The secondaries are numerous, thin, and parallel, as in lanceolate fig leaves of the *Ficus elastica* type. The younger leaves are much less elongated, being ovate-lanceolate in outline as shown in Plate XXIV, figure 6. This specimen is 8 centimeters in length by 3 centimeters in maximum width, and the surface is dotted with the leaf spots caused by a species of Sphærites. This fig is the most abundantly represented fossil at the locality 10 miles south of Macon.

Among the 600 or more described living species of Ficus which range over the warmer regions of the whole world, and among 300, more or less, fossil species known, which range from the Cretaceous to the Pleistocene, it would be possible to mention many whose foliage greatly resembles that of the present species, but it is hardly worth while to do more than point out that a number of modern tropical American species have foliage very close to this Eocene form. Various modern species of Ficus have been shown to owe their distribution to fruit-eating birds, and this may well have been the means by which the present species migrated along the Claiborne coast.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Fiske property, Grovetown, Columbia County (collected by S. W. McCallie); 10 miles south of Macon, Twiggs County (collected by E. W. Berry).

Collection.—U. S. National Museum.

Order **CHENOPODIALES**.

Family **NYCTAGINACEÆ**.

Genus **PISONIA** Linné.

PISONIA CLAIBORNENSIS sp. nov.

Plate XXVIII, figure 3.

Description.—Leaf ovate, 1.5 centimeters in length by 0.8 centimeter in greatest width, which is a little more than halfway between the base and the apex. Apex obtusely pointed. Base cuneate, slightly more produced and more pointed than the apex. Margin entire. Petiole missing. Midrib rather stout in a leaf so small. Secondaries few, branching from the midrib at an acute angle, 45° or slightly less, and curving upward, camptodrome. Leaf substance thin but apparently coriaceous.

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[1] Die natürlichen Pflanzenfamilien, pt. 3, 1894.

This species, except for its smaller size, is very similar to *Pisonia eocenica*, described by Ettingshausen from the Eocene or lower Oligocene of the Tyrol.[1] Among living species it resembles *Pisonia floridana* Britton of the Florida keys, which is, however, somewhat more rounded apically, giving its leaves a more obovate outline. The fossil is identical in every particular with the smaller leaves of the modern Central American species *Pisonia macranthocarpa* Donnell Smith. Inasmuch as the fossil species is based upon the single specimen figured it is impossible to tell whether the specimen collected is below the average size for the species or not. Presumably the leaves did not grow more than 50 per cent larger than the one figured. In *Pisonia macranthocarpa* the leaves vary considerably in size, some being larger than the fossil and others only one-third its size. Many are almost identical in size.

Several modern species are probably dispersed through the agency of ocean currents, and the same means of distribution may have been adopted by *Pisonia clairbornensis*, for many of its associates seem to have been similarly adapted for sea voyages.

Members of the genus are not rare in the fossil state. The oldest recorded species is based on leaves described by Velenovsky from the Chlomeker sandstone near Leipa, Bohemia, as *Pisonia atavia*.[2] These are of Upper Cretaceous and probably Senonian age, and if collected at a homotaxial horizon in this country would be referred to the genus Persoonia Swartz.[3] No other Cretaceous leaves have been referred to Pisonia,[4] although Lesquereux referred the only American species ever described, *Pisonia racemosa*,[5] to the Laramie. The material came from the "Black Buttes beds" of Wyoming, whose exact age has never been settled, although it may be basal Eocene. This species, which was based both on leaves and on fruiting specimens, had somewhat larger, more rounded leaves, and more ascending secondaries than the Georgia fossil. Five species recorded from the European Tertiary have the following distribution:

Pisonia lancifolia Heer, Flora Tertiaria Helvetiæ, vol. 2, 1856, p. 75, Pl. LXXXVIII, fig. 4; Tortonian of Switzerland.

Pisonia ovata Ludwig, Palæontographica, vol. 8, 1859, p. 107, Pl. XLIV, figs. 1 and 2; Oligocene of Hesse.

Pisonia bilinica Ettingshausen, Die fossile Flora des Tertiär-Beckens von Bilin, pt. 1, 1867, p. 89, Pl. XXIX, figs. 2 and 4; Miocene of Bohemia.

Pisonia radobojana Ettingshausen, Beiträge zur Kenntniss der fossile Flora von Radoboj, 1870, p. 877; Sarmatian of Croatia (leaves and fruit).

Pisonia eocenica Ettingshausen, previously mentioned; leaves and fruit in the lignites of Häring in the Tyrol. These beds are referred to the Ligurian by Gumbel and Friedrich, to the Stampian by De Lapparent, and to the Sannoisian by Douxami and Marty. The same species has been identified in the Oligocene of Saxony, Styria, Dalmatia, and Switzerland, and in the Miocene of Styria and Carniola. Massalongo records it from the Messinian of Italy.

The modern species of Pisonia are numerous and occur in the tropics of both hemispheres. They are largely developed in Central and tropical South America and several species appear in the West Indies and Antilles. Heimerl[6] divides the genus into six sections, some of which should undoubtedly be given generic rank; in fact, Britton[7] proposes to form from the West Indian, Bahaman, and Antillean species the genus Torrubia Velloso (Fl. Flum., 1825, p. 139), restricting Pisonia to vines to correspond with the type species *Pisonia aculeata* Linné.

Foreign usage and geologic considerations, which are even more important, make it inadvisable to follow too closely the innovations of systematists dealing only with existing flora; and especially where use of one or another name for closely related genera is in question, it is believed that a somewhat conservative course is the more desirable. The present species is therefore referred to Pisonia.

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[1] Die tertiäre Flora von Häring in Tirol: Abhandl. K.-k. geol. Reichsanstalt, vol. 2, Abth. 3, 1853, p. 43, Pl. XI, figs. 1-22.

[2] Die Flora böhmischen Kreideformation, pt. 4, 1885, p. 6, Pl. VIII, figs. 13 and 14.

[3] Cf. *Persoonia lesquereuxii* Knowlton, The flora of the Dakota group: Mon. U. S. Geol. Survey, vol. 17, 1892, p. 89, Pl. XX, figs. 10–12.

[4] The writer has recently described (Bull. Torrey Bot. Club, vol. 37, 1910, p. 191) a well-characterized Cretaceous species of Pisonia from the Black Creek formation of North Carolina, and the genus has also been found to be represented at various Tertiary horizons in the Mississippi embayment area.

[5] The Tertiary flora, 1878, p. 209, Pl. XXXV, fig. 4.

[6] Engler, A., and Prantl, K., Naturlichen Pflanzenfamilien, vol. 3, Abth. 1, 1889.

[7] Bull. Torrey Bot. Club, vol. 31, 1904, pp. 611–615.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Phinizy Gully, Columbia County; 10 miles south of Macon, Twiggs County. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Order ROSALES.

Family MIMOSACEÆ.

Genus MIMOSITES.

MIMOSITES GEORGIANUS sp. nov.

Plate XXVII, figures 5–9.

Description.—Leaflets of small size, ovate-lanceolate in outline, somewhat inequilateral, sessile, ranging from 2 to 3.8 centimeters in length and from 0.5 to 0.8 centimeter in maximum width, which may be in the apical or basal portion of the leaf or halfway between. Apex rounded or obtusely pointed. Base somewhat rounded or cuneate and pointed. Some of the leaves are perfectly symmetrical, others are somewhat extended apically, and still others have the base slightly extended. Margins entire. Midrib fairly stout below, thin above. Venation not seen.

These small leaflets are common at the Phinizy Gully locality but rare at the other Claiborne outcrops. They are almost identical with the leaflets of various modern Mimosaceæ. The fossil species of Mimosites are numerous and many species are contained in undescribed collections from the Wilcox group in the Mississippi embayment area.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group). Phinizy Gully, Columbia County, Ga. (collected by E. W. Berry); Grovetown (collected by T. W. Vaughan); 10 miles south of Macon, Twiggs County (collected by E. W. Berry).

Collection.—U. S. National Museum.

Order SAPINDALES.

Family DODONÆACEÆ.

Genus DODONÆA Linné.

DODONÆA VISCOSOIDES sp. nov.

Plate XXVIII, figures 4–8.

Description.—Leaves somewhat variable in shape, obovate in general outline, ranging from 4 to 7.5 centimeters in length by 1 to 2 centimeters in greatest width, which is usually above the center of the leaf. Sessile or nearly so. Apex rounded, in many specimens broadly; base extended, more or less narrowly cuneate with straight sides. Texture coriaceous. Midrib medium, becoming attenuated apically. Secondaries slender, commonly obscure, particularly in impressions of the upper surface of the leaves; 6 to 10 pairs, indifferently opposite, subopposite, and alternate, camptodrome; they branch from the midrib at angles which may be as small as 12° or as large as 70°, the basal ones becoming very ascending in specimens in which the base is much produced; the normal angle of divergence is about 45°. The basal secondaries branch near the base of the leaf and take a nearly straight ascending course parallel with the leaf margin and 1 to 2 millimeters from it, connecting almost a third of the length of the leaf from the base with a short outwardly and downwardly directed branch from the secondary next above. The other secondaries are placed at regular intervals and are more or less straight halfway to the margin, at which point they curve upward in a wide arch to joint an outwardly directed branch from the next succeeding secondary; beyond this they form a series of very small arches parallel with the margin and of a caliber which might well be termed tertiary. Tertiaries straight, lateral, or transverse in direction. Areolation fine, four or five sided.

This species is one of the commonest forms found in the Georgia Eocene, and apparently will prove a useful type fossil for this horizon, as it occurs at all the localities where fossil plants have been observed in the Claiborne of Georgia. The collection contains 10 specimens from the locality south of Macon, a large number from Phinizy Gully, and several on the reverse of one of the figured specimens of Thrinax from the Fiske property at Grovetown. Fragments of these leaves were also observed at other localities in the vicinity of Grovetown, where they were too poorly preserved to warrant being collected.

About 15 fossil species of Dodonæa have been described, and all are European but one, which is based on a rather doubtful fruit from Florissant, Colo., that is probably an Ulmus.[1] Seven of these 15 species are Oligocene, embracing both leaves and characteristic fruits and recorded from Styria, Prussia, France, Tyrol, and Switzerland. Seven are Miocene, including both leaves and fruit and coming from Baden, Croatia, Switzerland, Prussia, and Bohemia. Of these European forms *Dodonæa vetusta* Heer,[2] from the Aquitanian of Switzerland, and *Dodonæa prisca* Weber,[3] from the Aquitanian of Rhenish Prussia, are quite similar to the Georgia species and clearly represent the same type of leaf, although they show marked specific differences. It seems probable that some of the leaves from the American Eocene and the European Gypse (Ligurian) commonly referred to the willow oaks, represent Dodonæa. For example, Saporta describes two species of Dodonæa fruits from St. Zacharie, France, but no leaves, although the late Eocene and early Oligocene have furnished a number of suggestive leaves of this genus which have been usually referred to Quercus.

In the modern flora there are about 50 species of Dodonæa, more than 40 of these being Australian. A single species is found in the Hawaiian Islands and another in Madagascar. The Claiborne form closely resembles the mdoern *Dodonæa viscosa* Linné, which is found in peninsular Florida and on the keys, as well as in the oriental and occidental tropics, and which ranges as far north as Bermuda (latitude 32°), where it frequents the inner edges of the sand dunes. It is a small sapindaceous tree of the "beach jungle" and is one of the prominent forms in the tropical plant association named by Schimper the Barringtonia formation. It is protected from the strong isolation by varnished leaves with a thick epidermis and reduced stomata. Like many other strand plants, it is distributed largely through the agency of ocean currents.

As is true of numerous other late Cretaceous and Tertiary dicotyledonous genera, the former world-wide range of Dodonæa has given place to modern massing of its species in a single region in the southern hemisphere with only a few outlying and scattered species in other regions, to witness its former cosmopolitanism.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group). Phinizy Gully, Columbia County (collected by E. W. Berry); Grovetown, Columbia County (collected by S. W. McCallie and T. W. Vaughan); 10 miles south of Macon on Macon-Marion public road, Twiggs County (collected by S. W. McCallie and E. W. Berry).

Collection.—U. S. National Museum.

Family SAPINDACEÆ.

Genus SAPINDUS Linné.

SAPINDUS GEORGIANA sp. nov.

Plate XXVII, figures 11 and 12.

Description.—Leaflets small, lanceolate, falcate, 4 to 5.5 centimeters in length by 0.5 to 0.9 centimeters in greatest width, which is in the central part of the leaf. Apex and base both acuminate. Margin entire. Midrib stout below, becoming thin above. Secondaries, six to eight alternate pairs, branching from the midrib at an acute angle and curving upward, camptodrome, very fine and made out with difficulty.

There are more than 50 fossil species of Sapindus, ranging from the Cenomanian of America, Europe, and Greenland through the various Tertiary horizons to the Pleistocene. Among these species are three which approach the Georgia species—*Sapindus affinis* Newberry, *Sapindus angustifolius* Lesquereux, and *Sapindus stellariæfolia* Lesquereux. *Sapindus affinis* Newberry,[4] though perfectly distinct, in its smaller leaflets somewhat resembles the broader forms from Georgia. *Sapindus angustifolius* Lesquereux,[1] a Florissant, Colo., species which has been identified (probably erroneously) in the "Eolignitic" of Kentucky and Louisiana by Lesquereux and Hollick, respectively, is also very similar to the broader Georgia leaves. Finally, *Sapindus stellariæfolius* Lesquereux,[2] from Florissant, very closely approaches the Georgia species. It is, however, somewhat smaller, although it preserves the same general outlines, and according to Cockerell is not of Green River age, as suggested by Lesquereux, but of late Miocene, which serves to emphasize its specific distinctness.

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[1] Lesquereux, Leo, The Cretaceous and Tertiary floras, 1883, p. 182, Pl. XXXVI, fig. 5.

[2] Flora Tertiaria Helvetiæ, vol. 3, 1859, p. 64, Pl. CXXI, figs. 13, 14.

[3] Weber, C. O., Palæontographica, vol. 2, 1852, p. 85, Pl. V, fig. 8.

[4] Newberry, J. S., The later extinct floras of North America: Mon. U. S. Geol. Survey, vol. 35, 1898, p. 116, Pls. XXX, fig. 1, and XL, fig. 2.

The modern species of Sapindus number about 10; they inhabit warm temperate and tropical Asia and America. At least four species are found within the limits of the United States, and it would not be difficult to select leaflets from the common *Sapindus marginatus* Willdenow from the same area as the fossil species which would approach it very closely. The fossil is, however, more nearly related in all probability to *Sapindus saponaria* Linné, a common West Indian and South American tree which reaches the Florida keys and which has become a widespread member of the littoral flora through the agency of ocean currents. Hemsley records an instance of seeds of this species which were washed ashore on the south coast of Bermuda, germinating after their ocean voyage of about 900 miles (?).

A number of additional comparisons may be suggested, as, for example, with the leaves, so common in the Oligocene of Europe, which are referred to the Australian myrtaceous genus Callistemon R. Brown and to Callistemophyllum Ettingshausen. Among existing species the leaves of *Sapindus georgiana* may also be compared with those of *Gomphia linearis* of the South American Ochnaceæ and *Rhus lanceolatea* A. Gray, a Texas species of Anacardiaceæ.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group). Phinizy Gully, Columbia County, Ga. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Order **THYMELEALES.**

Family **LAURACEÆ.**

Genus **MALAPOENNA** Adanson.

MALAPOENNA sp.

Plate XXVII, figure 10.

Description.—A single poorly preserved lauraceous fruit was obtained from the locality south of Macon. It is too poor for adequate description, and is referred with hesitation to the genus Malapoenna.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), 10 miles south of Macon, Twiggs County, Ga. (Collected by E. W. Berry.)

Collection.—U. S. National Museum.

Order **MYRTALES.**

Family **RHIZOPHORACEÆ.**

Genus **RHIZOPHORA** Linné.

RHIZOPHORA EOCENICA sp. nov.

Plate XXIX, figures 1 and 2.

Description.—Leaves of small size (presumably young) and of medium size, elliptical in outline, rounded or obtusely pointed at the apex, a few somewhat emarginate smaller-sized variants from the normal form. The base slightly narrowed and broadly cuneate. Margins entire. Length about 7 to 8 centimeters; greatest width about 3.3 centimeters. Texture coriaceous, especially in the leaf shown in figure 1, Plate XXIX, in which the margins were apparently somewhat revolute. Midrib and petiole extremely stout. Secondary venation immersed and not seen.

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[1] Lesquereux, Leo, The Tertiary flora, 1878, p. 265, Pl. XLIX, figs. 2–7.

[2] Idem, p. 264, Pl. XLIX, fig. 1.

Leaves of this species are not common in the collections, probably because the collections are small and far from representative. The species is, however, of peculiar interest in that it sheds much light on the environment of the Claiborne flora of Georgia. Because of this great care has been taken to compare the present fossils with the leaves of all living or extinct forms which might be expected to occur in the latitude of Georgia at this stage of the Eocene. The species is obviously new to science, and it shows so many points of contact with the modern forms of Rhizophora, especially with *Rhizophora mangle* Linné of the American tropics, that its reference to this genus seems clearly warranted. With the exception of a single specimen of Rhizophora described by Massalongo[1] from the later Tertiary (Messinian) of the east coast of Italy, and a form referred to this genus by Ettingshausen, this is the only known fossil representative of this widespread modern genus. The form determined by Ettingshausen came from the Ligurian-Aquitanian of Austria, and was compared by him with the existing *Rhizophora parvifolia* Roxburg, of the East Indies.[2] The similarity of this form to various members of the Myrtaceæ and Leguminosæ, however, caused Schenk[3] to express doubt of Ettingshausen's identification.

It is possible that in the past leaves of this genus may not have been recognized when collected; the leaves from the "Eolignitic" which Lesquereux[4] identified with *Quercus chlorophylla* Unger are almost certainly not that species and are very similar to Rhizophora leaves. Not having seen the specimens, the writer is not justified in doing more than to call attention to this possible relation.

There are three existing species of Rhizophora. *Rhizophora mangle* Linné of the American tropics is found as far north as Mosquito Inlet and Cedar Key in peninsular Florida and at the mouth of the Mississippi; it also extends from the Mexican coast for some distance along the coast of Texas. It occurs throughout the Bahamas and West Indies and very generally throughout Central America and northern South America, having in comparatively recent times extended its range northward through the Bahamas to Bermuda. On the west coast it is found northward to Lower California and southward to the Galapagos Islands. *Rhizophora mucronata* Lamarck ranges from southern Japan to northern Australia and westward to east Africa; *Rhizophora conjugata* Linné is confined to tropical Asia. Doubtless modern systematists will differentiate additional specific forms, but judging by the rather uniform habits of these plants such differentiation will be based on minor characters. The mangrove plants possess the singular ability to flourish in sea water, and their manner of life and development have become well adapted both structurally and physiologically to their mode of existence, so that they have become widely disseminated and individually abundant; in fact, they are the most remarkably specialized plants for this habitant known, and their specialization was in a measure reached in the Eocene. They do much work as makers of land, as has often been described, and they are especially well developed on low shores around the heads of tropical or subtropical bays and estuaries. (See Pl. XVI, p. 160.) It is believed that the Grovetown locality was well toward the northern limit of the range of mangrove swamps in Claiborne time and that they were not so prominent an ecologic feature there as they evidently were farther south. Presumably there were some such swamps in the Grovetown estuary and elsewhere along the Claiborne coast from which the present leaves were derived, and possibly the lignite deposits a few miles southwest of Grovetown may represent such a swamp in place. The shores of this estuary were for considerable distances sandy, made up of the reworked sands of the Lower Cretaceous, as is shown by the fossil plants collected, for plants characteristic of the beach jungle predominate over those characteristic of mangrove swamps.

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[1] Studii sulla flora fossile e geologia stratigraphica del Semigalliese, 1859, p. 407.

[2] Die Tertiäre Flora von Häring in Tirol, 1853, p. 82, Pl. XXVII, figs. 28 and 29.

[3] Zittel's Handbuch, Abth. 2, 1890, p. 632.

[4] Proc. Am. Philos. Soc., new ser., vol. 13, 1869, p. 416, Pl. XVII, figs. 5–7.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group), Phinizy Gully, Columbia County, Ga. (collected by E. W. Berry); a well 13½ miles west of Sandersville, Washington County, Ga. (collected by S. W. McCallie); a locality 10 miles south of Macon, Twiggs County, Ga. (collected by E. W. Berry).

Collection.—U. S. National Museum.

Family COMBRETACEÆ R. Brown (TERMINALIACEÆ J. St. Hilaire)

Genus TERMINALIA Linné.

TERMINALIA PHÆOCARPOIDES sp. nov.

Plate XXIX, figure 3.

Description.—Leaves of medium and large size, broadly obovate in general outline with a rounded or pointed apex and a cuneate base. Margins entire. Length about 15 or 16 centimeters, and greatest width, which is above the middle, about 7 or 8 centimeters. Midrib stout. Secondaries about 8 pairs, subopposite or alternate, branching from the midrib at angles of about 50° and curving upward, approximately parallel, camptodrome. Tertiary venation not seen. As the remains of this species are merely impressions the texture can not be determined.

In a more northern flora this species would doubtless be compared with a Magnolia, and possibly some fossil species of Magnolia may be profitably compared with Terminalia. Otherwise the abundance of Terminalia in the European Tertiary, where it furnishes both leaves and characteristic fruits, and its absence from America is difficult to understand.

The present species is very similar to the modern widespread *Terminalia catappa* Linné if the apical portion, which is unfortunately missing, is broad and rounded like the outside dotted line in the figure; and is very similar to the modern *Terminalia phæocarpa* Eichler of northern South America if the outline corresponds to the inner dotted line in the figure.

The modern species of Terminalia are all tropical and number more than 100 forms, distributed among the various continents in the following proportions according to Engler and Prantl: America, 24; Asia, 27; Madagascar, 16; Africa, 17; Australia, 19. One indigenous species, *Terminalia buceras,* reaches the United States; it is common along the shores of the Caribbean Sea, extending northward through the West Indies to Elliotts Key, Fla., and growing generally on coral soil.

The present species is the only known American fossil member of this genus. About a dozen species are described from Europe, the oldest, not positively identified, coming from the Upper Cretaceous of Bohemia. One species is described from the lower Oligocene of Aix (Provence, France) and the others range in age from the Oligocene to the Pliocene and are represented by both leaves and fruit. They are especially common along the extended late Tertiary seacoast of south-central Europe, the Messinian showing four species, the Sarmatian three, and the Astian two. The European fossil form nearest the Georgia form, though the resemblance is not especially close, is *Terminalia radobojensis* Unger, which has a recorded range from the Tongrian to the Astian.

Terminalia catappa is one of the prominent elements in the oriental littoral forest or beach jungle of the Tropics (Barringtonia formation of Schimper), its buoyant fruits having enabled it to become widespread within its limits of range through the agency of ocean currents. In this connection attention should be called to the two species *Magnolia hilgardiana*[1] and *Magnolia laurifolia*[2] described by Lesquereux from the "Eolignitic" of the Mississippi embayment. Either of these species may find its nearest modern affinity among the various species of Terminalia rather than Magnolia, and it is perhaps significant that Lesquereux compared the second of these to the European Tertiary species *Terminalia radobojensis* Unger.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group). Fiske property, Grovetown, Columbia County. (Collected by S. W. McCallie.)

Collection.—U. S. National Museum.

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[1] Lesquereux, Leo, Proc. Am. Philos. Soc., new ser., vol. 13, 1869, p. 421, Pl. XX, fig. 1.

[2] Idem, p. 421, Pl. XX, figs. 2 and 3.

Genus CONOCARPUS Linné.

CONOCARPUS EOCENICA sp. nov.

Plate XXIX, figures 4–7.

Description.—Leaves of medium and small size, lanceolate and usually inequilateral in outline, with an obtusely pointed apex and a similarly pointed base, margins entire. Length 6 to 10 centimeters; greatest width, which is about midway between the apex and the base, 1.5 to 2.6 centimeters. Midrib stout. Secondaries remote, about six pairs, opposite or subopposite, branching from the midrib at angles of about 50°, extending outward and then sweeping upward in a broadly rounded curve, parallel with the margin and approximately parallel with their fellows, ultimately camptodrome. Tertiaries fine forming a polygonal areolation.

This species is represented by several specimens from both localities near Grovetown and is obviously related to Conocarpus both in outline and in venation, as well as probably in habitat.

Conocarpus is a monotypic genus in the existing flora, the single species, *Conocarpus erectus* Linné, being widespread along low muddy or sandy tropical shores in Central and South America and on the west coast of Africa (Guinea and Senegambia). It is found in the Galapagos Islands and extends northward from the West Indies to the Florida Keys and to Bermuda, where it is found on the sand dunes. Its distribution has been effected through the agency of ocean currents. The fossil form appears to be closest to the modern variety *arboreus* Grisebach of Central America. The modern species is not only a typical member of the mangrove association of Africa and America, but much more widespread than the mangroves, for it is equally a plant of strand and dunes. The texture and anatomy of its leaves differ somewhat according to their degree of exposure to the rays of the sun.

No other fossil species of Conocarpus are known, but this species may be compared with certain European Tertiary forms referred to the allied genus Eugenia, of which several have been described, more especially from the Oligocene. Both *Eugenia aizoon* Unger and *Eugenia haeringiana* Unger are somewhat similar to the Georgia leaf.

Occurrence.—Congaree clay member of McBean formation (of Claiborne group). Phinizy Gully, Columbia County, Ga. (collected by E. W. Berry); Fiske property, Columbia County, Ga. (collected by S. W. McCallie); 10 miles south of Macon, Twiggs County, Ga. (collected by E. W. Berry).

Collection.—U. S. National Museum.

EOCENE FLORAS OF EUROPE AND NORTH AMERICA.

A large number of species of plants have been described from various Eocene localities in Europe, but the data for an accurate comparison of these floras with that of the Claiborne are most incomplete. This lack of data is due in a measure to the fact that the bulk of the European Eocene deposits are marine, and the usual difficulties in correlation present themselves when the attempt is made to compare isolated fluviatile and lacustrine plant-bearing beds with their marine equivalents where the standards and nomenclature are largely those of invertebrate paleontology. This is particularly true of the Eocene, because the most complete paleobotanic section of this age, which is checked by paleozoology, has remained to a large extent undescribed. The splendid series of plant-bearing horizons of the south of England have, with the exception of sporadic descriptions of certain local florules by De la Harpe, Heer, Ettingshausen, and others, and the work of J. Starkie Gardner on the ferns and conifers, remained unknown down to the present. It seems remarkable that only two Englishmen, Bowerbank and Gardner, have devoted any considerable attention to these floras, and the latter failed to complete his work, so that in many ways the most interesting part of the British Eocene flora, certainly the most useful for purposes of correlation, remains unknown to science except for various antiquated and scattered references.

A brief sketch will be given of the present state of knowledge of European Eocene floras, commencing with the earliest and giving special attention to the floras more nearly homotaxial with the American Claiborne.

The basal Eocene beds, Montian and Thanetian stages (Paleocene of Schimper and Saporta and lower Landenian of the last edition of De Lapparent) furnish a fairly representative flora described from the plastic clay of Trieu de Leval (Hainaut) Belgium by Marty,[1] from the travertines of Sézanne, France, by Saporta,[2] and from the marnes heersiennes of Gelinden, Belgium, by Saporta and Marion.[3] In addition to these two florules a few scattered algæ and fragments of land plants are preserved in the marine deposits of these stages.

The lower Eocene beds, Sparnacian and Ypresian[4] stages, include in earlier deposits the flora found in the Oldhaven, Woolwich, and Reading beds of England, largely unstudied, and the small flora recently described by Fritel[5] from the Paris basin. In their later deposits (Cuisian of Dollfuss, 1909, in part the Londinian of Mayer-Eymar, 1857) they include the flora of the grès de Belleu in France[6] and those of Alum Bay and the London clay in England. The London clay fossils are largely lignitized and pyritized fruits and seeds from the Isle of Sheppey and leaf impressions from the pipe clay of Alum Bay. These have never been figured or carefully studied, but the following old list will give some idea of the Alum Bay flora:

Alum Bay flora as determined by Ettingshausen.[7]

Acacia brittanica Ettingshausen and Gardner.
  sotzkiana Unger.
Acer eocenicum Ettingshausen and Gardner.
  præ-decipiens Ettingshausen and Gardner.
Adenopeltis alumensis Ettingshausen and Gardner.
Alyxia europæa Ettingshausen and Gardner.
Amygdalus pereger Unger.
  præ-œningensis Ettingshausen and Gardner.
  tenue-striata Ettingshausen and Gardner.
Andromeda protogæa Unger.
Anemia subcretacea Saporta.
Anona cyclosperma Ettingshausen and Gardner.
  elongata Ettingshausen and Gardner.
Apocynophyllum grande Ettingshausen and Gardner.
  haeringianum Ettingshausen.
  præ-amsonia Ettingshausen and Gardner.
  titaniæ Ettingshausen and Gardner.
Aralia primigenia De la Harpe.
Aristolochia alumensis Ettingshausen and Gardner.
Aronium eocenicum Ettingshausen and Gardner.
Artocarpidium grandifolium Ettingshausen and Gardner.
  integrifolium Unger.
Arundo goepperti (Muenster).
Banksia dillenioides Ettingshausen.
  ungeri Ettingshausen.
Bombax menjæ Ettingshausen and Gardner.
  sagorianum Ettingshausen.
  tenuinerve Ettingshausen and Gardner.
Bumelia dryadum Ettingshausen and Gardner.
  oreadum Unger.
Cæsalpinia æmula Heer.
  haidingeri Ettingshausen.
Callicoma fornacis Ettingshausen and Gardner.
Callistemophyllum diosmoides Ettingshausen.
Callistemophyllum elegans Ettingshausen and Gardner.
  melaleucæforme Ettingshausen.
  obtusum Ettingshausen and Gardner.
Callitris curta Bowerbank.
Carpolithes alumensis Ettingshausen and Gardner.
  crassipes Ettingshausen and Gardner.
  elliptico-valvatus Ettingshausen and Gardner.
  napærum Ettingshausen and Gardner.
  præboveyanus Ettingshausen and Gardner.
  tricoccinus Ettingshausen and Gardner.
Cassia berenices Unger.
  fischeri Heer.
  feroniæ Ettingshausen.
  hyperborea Unger.
  memnonia Unger.
  phaseolites.
  præ-lignitum Ettingshausen and Gardner.
  præ-memnonia Ettingshausen and Gardner.
  præ-phaseolites Ettingshausen and Gardner.
  præ-sagorina Ettingshausen and Gardner.
  præ-stenophylla Ettingshausen and Gardner.
  pseudo-glandulosa Ettingshausen.
  sagoriana Ettingshausen.
  ungeri De la Harpe.
  zephyri Ettingshausen.
Cecropia eocenica Ettingshausen and Gardner.
Cedrela primigenia Ettingshausen and Gardner.
Celastrophyllum undulatium Ettingshausen and Gardner.
Celastrus elænus Unger.
  fengæ Ettingshausen and Gardner.
  myricinus Ettingshausen and Gardner.
  præ-europæus Ettingshausen and Gardner.
  salidæ Ettingshausen and Gardner.
  tafnis Ettingshausen and Gardner.

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[1] Études sur les végétations fossiles du Trieu de Leval (Hainaut): Mém. Musée d'hist. nat. Belgique, vol. 5, 1907. This is an older flora than that of Gelinden or Sézanne and is said to show affinities with tropical American flora.

[2] Prodrome d'une flore fossile des travertins anciens de Sézanne: Mém Soc. géol. France, 2d ser., vol. 8, 1868, pp. 289–436, Pls. XXII–XXXVI.

[3] Saporta, G. de, and Marion, A. F., Essai sur l'état de la végétation à l'époque des marnes heersiennes de Gelinden: Mém. cour. et des Sav. étrang. Acad. roy. Belgique, vol 37, 1873, No. 6, pp. 1–94, Pls. I–XII. Revision de la flore heersienne de Gelinden, etc.: Idem, vol. 41, 1878, No. 3, pp. 1–112, Pls. I–XIV.

[4] These and other Eocene floras of the Paris basin are at present being admirably revised by Prof. P. H. Fritel, of the Museum of Natural History, Paris.

[5] Fritel, P. H., Étude sur les végétaux fossiles de l'étage Sparnacien du bassin de Paris: Mém. Soc. géol. France, vol. 16, 1910, No. 40.

[6] Watelet, A., Description des plantes fossiles du bassin de Paris, 1866.

[7] Proc. Roy. Soc. London, vol. 30, 1880, pp. 228–236.

- Celtis woodwardi Ettingshausen and Gardner.
- Ceratopetalum crassipes Ettingshausen and Gardner.
  - haeringianum Ettingshausen.
  - manni Ettingshausen and Gardner.
- Chrysodium lanzeanum (Visiani).
- Cinchonidium lanceolatum Ettingshausen and Gardner.
  - præ-bilinicum Ettingshausen and Gardner.
  - præ-latifolium Ettingshausen and Gardner.
- Cinnamomum eocenicum Ettingshausen.
  - polymorphum Al. Braun.
  - rossmæssleri Heer.
- Cissus auroræ Ettingshausen and Gardner.
  - celastrifolia Ettingshausen and Gardner.
- Clerodendron europæum Ettingshausen and Gardner.
- Comptonia acutiloba (Sternberg).
- Copaifera harpei Ettingshausen and Gardner.
  - prisca Ettingshausen and Gardner.
  - veledæ Ettingshausen and Gardner.
- Cornus atlantica Ettingshausen and Gardner.
- Cupania corrugata Bowerbank.
  - depressa Bowerbank.
  - grandis Bowerbank.
  - lobata Bowerbank.
  - subangulata Bowerbank.
  - tumida Bowerbank.
- Cupressinites globosus Bowerbank.
- Cyperites eocenicus Ettingshausen and Gardner.
- Dalbergia cyclophylla Ettingshausen and Gardner.
  - eocenica Unger.
  - haeringiana Ettingshausen.
  - longifolia Ettingshausen and Gardner.
  - primæva Unger.
  - ungeri Ettingshausen.
- Daphne aquiranica Ettingshausen.
- Daphnogene anglica Heer.
  - veronensis Massalongo.
- Diospyros eocenica Ettingshausen and Gardner.
- Dodonea præ-salicites Ettingshausen and Gardner.
  - subglobosa Ettingshausen and Gardner.
- Elæodendron dubium Ettingshausen.
- Eucalyptus haeringiana Ettingshausen.
  - oceanica Unger.
- Eugenis apollinis Unger.
- Fagus intermedia Ettingshausen and Gardner.
- Ficus arenacea Lesquereux.
  - bowerbankii De la Harpe.
  - bumeliæfolia Ettingshausen.
  - cisæ Ettingshausen and Gardner.
  - deleta Ettingshausen and Gardner.
  - falconeri Heer.
  - granadilla Massalongo.
  - hydrarchos Unger.
  - inguionis Ettingshausen and Gardner.
  - jynx Unger.
  - lanceolata Heer.
  - morrisii De la Harpe.
  - nerthi Ettingshausen and Gardner.
  - planicostata Lesquereux.
  - præ-arcinervis Ettingshausen and Gardner.
  - præ-lanceolata Ettingshausen and Gardner.
  - reussii Ettingshausen.
  - rhamnoides Ettingshausen and Gardner.
  - wudgæ Ettingshausen and Gardner.
- Flabellaris sp.
- Fraxinus jovis Ettingshausen and Gardner.
  - præ-savinensis Ettingshausen and Gardner.
- Glycyrrhiza deperdita Unger.
- Glyptostrobus europæus Brongniart.
- Grevillea hermionis Ettingshausen and Gardner.
- Grewiopsis integerrima Ettingshausen and Gardner.
- Hightea elliptica Bowerbank.
  - turbinata Bowerbank.
- Hiraea intermedia Ettingshausen and Gardner.
- Ilex atlantica Ettingshausen and Gardner.
- Juglandites cernuus Saporta.
- Juglans præ-parschlugiana Ettingshausen and Gardner.
  - sharpei De la Harpe.
- Lauris agathophyllum Unger.
  - haidingeri Ettingshausen.
  - jovis De la Harpe.
  - lalages Unger.
  - ocoteides Lesquereux.
  - primigenia Unger.
  - salteri De la Harpe.
  - socialis Lesquereux.
  - swoszowiciana Unger.
  - vetusta Saporta.
- Leguminosites callisemæfolium Ettingshausen and Gardner.
  - pachyphyllus Ettingshausen and Gardner.
- Lomatia brittanica Ettingshausen and Gardner.
- Magnolia stygia Ettingshausen and Gardner.
- Malpighiastrum banisterinum Ettingshausen and Gardner.
  - grandifolium Ettingshausen and Gardner.
  - præ-venosum Ettingshausen and Gardner.
- Marattia hookeri Ettingshausen and Gardner.
- Mimosites præ-cassiæformis Ettingshausen and Gardner.
- Myrica acuminata Unger.
  - haeringiana Unger.
  - lignitum Unger.
  - sagoriana Ettingshausen.
  - salicina Unger.
- Myrsine erdæ Ettingshausen and Gardner.
- Myrtus eocenica Ettingshausen and Gradner.
- Nelumbium buchii Ettingshausen.
- Notelæa primigenia Ettingshausen and Gardner.
- Nymphæa doris Heer.
- Nyssa alumensis Ettingshausen and Gardner.
  - europæa Unger.
  - præ-striolata Ettingshausen and Gardner.
- Olea brittanica Ettingshausen and Gardner.
- Palæolobium haeringianum Unger.
  - heterophyllum Unger.
  - præ-radobojense Ettingshausen and Gardner.
  - sotzkianum Unger.
- Persoonia eocenica Ettingshausen.
- Phaseolites eriosemæfolius Unger.
- Phyllites apocynoides Ettingshausen and Gardner.
  - arbutoides Ettingshausen and Gardner.
  - cecropioides Ettingshausen and Gardner.
  - crassipies Ettingshausen and Gardner.
  - densinervis Ettingshausen and Gardner.
  - elæocarpoides Ettingshausen and Gardner.
  - euphorbioides Ettingshausen and Gardner.
  - ficoides Ettingshausen and Gardner.
  - franguloides Ettingshausen and Gardner.

Phyllites freæ Ettingshausen and Gardner.
gargantuæ Ettingshausen and Gardner.
hederaceus Ettingshausen and Gardner.
hilticis Ettingshausen and Gardner.
hymenæoides Ettingshausen and Gardner.
lantanoides Ettingshausen and Gardner.
myrtaceus Ettingshausen and Gardner.
nimrodis Ettingshausen and Gardner.
nerthi Ettingshausen and Gardner.
sapindoides Ettingshausen and Gardner.
simaruboides Ettingshausen and Gardner.
syringæformis Ettingshausen and Gardner.
veledæ Ettingshausen and Gardner.
Physolobium antiquum Unger.
orbiculare Unger.
Pisonia eocenica Ettingshausen.
Pistacia brittanica Ettingshausen and Gardner.
Pittosporum eocenicum Ettingshausen and Gardner.
Planera ungeri Ettingshausen.
Podocarpus eocenica Unger.
Podogonium obtussissimum Ettingshasen and Gardner.
sheppyense Ettingshausen and Gardner.
Populus eocenica Ettingshausen and Gardner.
Porana œningenesis Al. Braun.
Proteoides crassipes Ettingshausen and Gardner.
Prunus druidum Ettingshausen and Gardner.
pygmæorum Ettingshausen and Gardner.
Pterospermites dentatus Ettingshausen and Gardner.
Pterospermum eocenicum Ettingshausen and Gardner.
Quercus bournensis Ettingshausen and Gardner.
drymeja Unger.
lonchitis Unger.
lyellii Heer.
præ-lonchitis Ettingshausen and Gardner.
præ-mediterranea Ettingshausen and Gardner.
viburnifolia Lesquereux.
Rhamnus acutangula Ettingshausen and Gardner.
præ-pomaderris Ettingshausen and Gardner.
præ-rectinervis Ettingshausen and Gardner.
Rhus atlantidis Ettingshausen and Gardner.
Rhus cyclophylla Ettingshausen and Gardner.
prisca Ettingshausen.
Rhytisma eucalypti Ettingshausen and Gardner.
priscum Ettingshausen and Gardner.
Sabal major Unger.
Salix præ-integra Ettingshausen and Gardner.
rhedæ Ettingshausen and Gardner.
tenuifolia Ettingshausen and Gardner.
Salmalia borealis Ettingshausen and Gardner.
Santalum acheronticum Ettingshausen.
microphyllum Ettingshausen.
osyrinum Ettingshausen.
salicinum Ettingshausen.
Sapindus angustifolius Lesquereux.
crassinervis Ettingshausen and Gardner.
eocenicus Ettingshausen and Gardner.
falcifolius Al. Braun.
Sapotacites emarginatus Heer.
eocenicus Ettingshausen and Gardner.
sideroxyloides Ettingshausen.
Saurauja robusta Saporta.
Sclerotium antiquum Ettingshausen and Gardner.
Sequoia couttsiæ Heer.
langsdorfii Brongniart.
Smilax lancifolia Ettingshausen and Gardner.
Sophora europæa Unger.
Sterculia labrusca Unger.
sigfridi Ettingshausen and Gardner.
Symplocos brittanica Ettingshausen and Gardner.
Ternstrœmia bilinica Ettingshausen.
eocenica Ettingshausen and Gardner.
Ulmus antiquissima Saporta.
plurinervia Unger.
Vaccinium acheronticum Unger.
eocenicum Ettingshausen and Gardner.
Vitis præ-tentonica Ettingshausen and Gardner.
Zizyphus integrifolius Heer.
pachyneuris Ettingshausen and Gardner.
ungeri Heer.
vetustus Heer.

Isle of Sheppey flora as determined by Ettingshausen.[1]

Acer sp.
Agave eocenica Ettingshausen and Gardner.
Amomum sheppyensis Ettingshausen and Gardner.
stenocarpum Ettingshausen and Gardner.
Amygdalus eocenica Ettingshausen and Gardner.
sporadum Ettingshausen and Gardner.
Apeiobopsis variabilis (Bowerbank).
Apocynophyllum sheppyensis Ettingshausen and Gardner.
Areca prisca Ettingshausen and Gardner.
recentior Ettingshausen and Gardner.
Aronium eocenicum Ettingshausen and Gardner.
Asterocaryum europæum Ettingshausen and Gardner.
Bactris prisca Ettingshausen and Gardner.
Bauhinia primigenia Ettingshausen and Gardner.
Callitris comptoni (Bowerbank).
curta (Bowerbank).
Carpolithes affinis Ettingshausen and Gardner.
amygdaloides Ettingshausen and Gardner.
atlantidis Ettingshausen and Gardner.
Carpolithes biococculatus Ettingshausen and Gardner.
bispermus Ettingshausen and Gardner.
breviangulatus Ettingshausen and Gardner.
brevicristatus Ettingshausen and Gardner.
bruceoides Ettingshausen and Gardner.
caryopsiformis Ettingshausen and Gardner.
caryotoides Ettingshausen and Gardner.
circumscriptus Ettingshausen and Gardner.
colletioides Ettingshausen and Gardner.
costatus Ettingshausen and Gardner.
cruciferinus Ettingshausen and Gardner.
disciformis Ettingshausen and Gardner.
folliculiformis Ettingshausen and Gardner.
franguloides Ettingshausen and Gardner.
hydrophylloides Ettingshausen and Gardner.
lineatus Ettingshausen and Gardner.
metrosideroides Ettingshausen and Gardner.
morrisii Ettingshausen and Gardner.
musæformus Etingshausen and Gardner.

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[1] Proc. Roy. Soc. London, vol. 29, 1879, pp. 388–396.

- Carpolithes napæarum Ettingshausen and Gardner.
  - nimrodis Ettingshausen and Gardner.
  - nyssæformis Ettingshausen and Gardner.
  - populoides Ettingshausen and Gardner.
  - pluriocculatus Ettingshausen and Gardner.
  - punctatostriatus Ettingshausen and Gardner.
  - radiotopunctatus Ettingshausen and Gardner.
  - reticulatorugosus Ettingshausen and Gardner.
  - subalatus Ettingshausen and Gardner.
  - sulcatus Ettingshausen and Gardner.
  - tenuepunctatus Ettingshausen and Gardner.
  - verrucosus Ettingshausen and Gardner.
  - websterioides Ettingshausen and Gardner.
  - zizyphoides Ettingshausen and Gardner.
  - zoroastri Ettingshausen and Gardner.
- Caulinites sheppyensis Ettingshausen and Gardner.
- Chamærops borealis Ettingshausen and Gardner.
- Cinchonidium priscum Ettingshausen and Gardner.
- Corchorites quadricostatus Ettingshausen and Gardner.
  - quinquecostatus Ettingshausen and Gardner.
- Corylus primigenia Ettingshausen and Gardner.
- Cotoneaster sheppyensis Ettingshausen and Gardner.
- Cucumites sheppyensis Ettingshausen and Gardner.
- Cupania corrugata (Bowerbank).
  - depressa (Bowerbank).
  - grandis (Bowerbank).
  - inflata (Bowerbank).
  - lobata (Bowerbank).
  - pygmæa (Bowerbank).
  - subangulata (Bowerbank).
  - tumida (Bowerbank).
- Cupressinites elongatus Bowerbank.
  - globosus Bowerbank.
  - recurvatis Bowerbank.
  - subfusiformis Bowerbank.
- Cyperites eocenicus Ettingshausen and Gardner.
- Diospyros eocenica Ettingshausen and Gardner.
  - pleadum Ettingshausen and Gardner.
- Elæis eocenica Ettingshausen and Gardner.
- Eucalyptus oceanica Unger.
- Eugenia eocenica Ettingshausen and Gardner.
- Euphorbiophyllum eocenicum Ettingshausen and Gardner.
- Faboidea acuta Bowerbank.
  - angustissima Bowerbank.
  - bifalcis Bowerbank.
  - complanata Bowerbank.
  - crassa Bowerbank.
  - crassicutis Bowerbank.
  - doliformis Bowerbank.
  - larga Bowerbank.
  - longiuscula Bowerbank.
  - marginata Bowerbank.
  - oblonga Bowerbank.
  - ovata Bowerbank.
  - pinguis Bowerbank.
  - plana Bowerbank.
  - planidorsa Bowerbank.
  - planimeta Bowerbank.
  - quadrapes Bowerbank.
  - robusta Bowerbank.
  - rostrata Bowerbank.
  - semicurvilinearis Bowerbank.
  - subdisca Bowerbank.
- Faboidea subrobusta Bowerbank.
  - subtenuis Bowerbank.
  - symmetrica Bowerbank.
  - tenuis Bowerbank.
  - ventricosa Bowerbank.
- Hightea elegans Bowerbank.
  - elliptica Bowerbank.
  - inflata Bowerbank.
  - minima Bowerbank.
  - orbicularis Bowerbank.
  - oviformis Bowerbank.
  - turbinata Bowerbank.
  - turgida Bowerbank.
- Hybothya crassa (Bowerbank).
- Illicium apollinis Ettingshausen and Gardner.
- Iriartea punctata Ettingshausen and Gardner.
  - striata Ettingshausen and Gardner.
- Juglans eocenica Ettingshausen and Gardner.
- Laurus lalages Unger.
- Lawsonia europæa Ettingshausen and Gardner.
- Leguminosites æquilateralis Bowerbank.
  - cordatus Bowerbank.
  - crassus Bowerbank.
  - curtus Bowerbank.
  - dimidiatus Bowerbank.
  - elegans Bowerbank.
  - enormis Bowerbank.
  - gracilis Bowerbank.
  - inconstans Bowerbank.
  - lentiformis Bowerbank.
  - lobatus Bowerbank.
  - longissimus Bowerbank.
  - planus Bowerbank.
  - reniformis Bowerbank.
  - rotundatus Bowerbank.
  - subquadrangularis Bowerbank.
  - subovatus Bowerbank.
  - trapeziformis Bowerbank.
- Liquidambar eocenicum Ettingshausen and Gardner.
- Livistona eocenica Ettingshausen and Gardner.
- Magnolia eocenica Ettingshausen and Gardner.
- Menispermatacites abutoides Ettingshausen.
- Metrosideros microcarpa Ettingshausen and Gardner.
- Mimosites brownianus Bowerbank.
- Musa eocenica Ettingshausen and Gardner.
- Nelumbium buchii Ettingshausen.
  - microcarpum Ettingshausen and Gardner.
- Nipa burtini (Brongniart).
  - elliptica (Bowerbank).
  - lanceolata (Bowerbank).
  - parkinsonis (Brongniart).
  - semiteres (Bowerbank).
- Nyssa eocenica Ettingshausen and Gardner.
- Œnocarpus sheppyensis Ettingshausen and Gardner.
- Petrophiloides conoideus Bowerbank.
  - imbricatus Bowerbank.
  - oviformis Bowerbank.
- Pinus sheppyensis Ettingshausen and Gardner.
- Podogonium sheppyenses Ettingshausen and Gardner.
- Proteoides bisulcatus Ettingshausen and Gardner.
- Prunus druidum Ettingshausen and Gardner.
  - prisca Ettingshausen and Gardner.
- Quercus drymeja Unger.

Quercus, eocenica Ettingshausen and Gardner.
lonchitis Unger.
Sabal dianæ Ettingshausen and Gardner.
dryadum Ettingshausen and Gardner.
major Unger.
oreadum Ettingshausen and Gardner.
Salisburia eocenica Ettingshausen and Gardner.
Sapindus eocenicus Ettingshausen and Gardner.
Sapotacites chrysophylloides Ettingshausen and Gardner.
mimusops Ettingshausen.
Sequoia bowerbankii Ettingshausen and Gardner.
Smilax pristina Ettingshausen and Gardner.
Solanites elegans Ettingshausen and Gardner.
Solenostrobus corrugatus (Bowerbank).
semiplotus (Bowerbank).
subangulatus (Bowerbank).
sulcatus (Bowerbank).
Sphæria flabellariæ Ettingshausen and Gardner.
Strychnos urani Ettingshausen and Gardner.
Symplocos radobojana Unger.
Theobroma nimrodis Ettingshausen and Gardner.
zoroastri Ettingshausen and Gardner.
Thlaspidium ovatum Ettingshausen and Gardner.
Tricarpellites aciculatus Bowerbank.
communis Bowerbank.
crassus Bowerbank.
curtus Bowerbank.
gracilis Bowerbank.
patens Bowerbank.
rugosus Bowerbank.
Thrinax bowerbankii Ettingshausen and Gardner.
var. elliptica.
var. globosa.
Victoria najadum Ettingshausen and Gardner.
sheppyensis Ettingshausen and Gardner.
Wetherellia variabilis Bowerbank.
Xulinosprionites latus Bowerbank.
zingiberiformis Bowerbank.

This list, though it leaves much to be desired, shows that the flora of this horizon indicates a considerably warmer climate than the floras which preceded it, though it is doubtful that it was as tropical in character as Gardner represented it to be.

The middle Eocene, with which the Claiborne is more directly comparable, is divided by De Lapparent into the Lutetian and Bartonian stages. The Lutetian, the lower part of the Parisian of D'Orbigny, is marked by an advance of the sea, both in Europe and America. In France the sea advanced southward beyond the old Suessonian shore line around Paris, to the west, and north into Belgium. A similar arm of the sea extended across the present site of the Pyrenees. Practically all Italy and a large part of Austria-Hungary were submerged and a great Mediterranean or Nummulitic sea extended from the Atlantic eastward to the Indian Ocean, over southeastern Europe, northern Africa, and southwestern Asia, and with possibly a narrow northern outlet to the Arctic Ocean across the Russian Empire. The calcaire grossier beds of the Paris basin are typically marine below, becoming lacustrine or fluviatile above (calcaire grossier supérieur). Bureau[1] has described a few plants from these beds, the number including species of Nitophyllum, Pandanus, Flabellaria, Sabal, Palmacites, Yucca, and Nuphar. In the upper beds at Trocadéro, near Paris (argile verte lignitifère), an estuary flora, largely undescribed, occurs. Species identified from this locality include Dryandra, *Euphorbiophyllum vetus*, *Nerium parisiensis*, *Ottelia parisiensis* (which is comparable with the Potamogeton described in this report), *Pandanus lutetianus*, and *Zizyphus pseudoungeri*. The characteristic large floating seeds of *Nipadites burtini*, also found at this place, suggest an environment like that of Grovetown. The Monte Bolca plant beds of Italy, with their numerous and large palms, are in general of character similar to these other localities. The plant beds of the Bagshot sands and Bournemouth clays of southern England, and possibly those of Antrim and Mull described by J. Starkie Gardner, also belong at about the same level. The south coast flora, of which the angiosperms have never been described or figured, includes the following forms:

FILICALES:
Acrostichum lanzæanum (Visani).
Adiantum apalophyllum Saporta.
Anemia subcretacea (Saporta) Ettingshausen and Gardner.
Asplenites præ-allosuroides Ettingshausen and Gardner.
Gleichenia hantonensis (Wanklyn) Ettingshausen and Gardner.
Glossochlamys transmutans Ettingshausen and Gardner.

FILICALES—Continued.
Goniopteris stiriaca (Unger) Ettingshausen and Gardner.
Hewardia regia Ettingshausen and Gardner.
Lygodum kaulfussi Heer.
Meniphyllum elegans Ettingshausen and Gardner.
Osmunda lignitum (Giebel) Heer.
Phegopteris bunburii (Heer) Ettingshausen and Gardner.
Phegopteris præ-cuspidata Ettingshausen and Gardner.

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[1] Études sur la flore fossile du calcaire grossier parisien, Mém. Soc. Philom., 1888, pp. 235–264, Pls. XXII and XXIII.

FILICALES—Continued.
- Phymatodes affine Ettingshausen and Gardner.
- Phymatodes polypodioides Ettingshausen and Gardner.
- Pteris bournensis Ettingshausen and Gardner.
- Pteris eocenica Ettingshausen and Gardner.
- Woodwardia? venosa Ettingshausen and Gardner.

CONIFERALES:
- Araucaria gœpperti Sternberg.
- Cupressus taxiformis Unger.
- Glyptostrobus (Gardner).
- Glyptostrobus eocenum (Gardner).
- Pinus bowerbankii Carruthers.
- Pinus dixoni Bowerbank.
- Podocarpus eocenica Unger.

CONIFERALES—Continued.
- Podocarpus? incerta Gardner.
- Sequoia couttsiæ Heer (considered an Arthrotaxopsis by Gardner).
- Sequoia tournalii (Brongnart) Saporta.

MONOCOTYLEDONÆ:
- Numerous specimens of both fan and feather palms (Iriartæa, Phœnix, Calamus, and Nipa).

DICOTYLEDONÆ:
- Castanea-like leaf (=Godoya? according to Gardner).
- Ficus.
- Myrica.
- Cinnamomum.
- Dioscorea.

The flora of the pottery clays and lignites of Bovey Tracey in Devonshire was fully described by Heer [1] in 1863, who referred it to the Aquitanian. This determination was questioned by J. Starkie Gardner,[2] who considered the Bovey Tracey flora to be of the same age as that from Bournemouth, or Lutetian. Notwithstanding the inadequacy of the evidence in support of Gardner's opinion, it was generally accepted, especially in Great Britain. Recently Clement and Eleanor M. Reid [3] have reexamined both the geology and the flora of Bovey Tracey and have corroborated Heer's conclusion that these thick deposits (160 meters) are a unit of upper Oligocene age. They are considered homotaxial with the Wetterau lignites of Germany (Aquitanian or lower Miocene of the fifth edition of De Lapparent).

The Bartonian or upper Parisian takes its name from the Barton clays of England (100 meters thick), with an undescribed flora, and there are scattered florules of this age from various localities in France and Italy. Such a florule from Brives in Velay has been partially described by Saporta.[4] It includes the following genera: Acacia?, Andromeda, Comptonia, Dryandra, Laurus, Leguminosites, Magnolia, Myrica, Myrsine, Phœnix, Populus, Quercus, Sabalites, Sapotacites, Sapindus, Sophora?, and Zanthoxylon?.

From Main, Anjou, and Vendée, in western France, Crié in various contributions [5] has described a flora of this age in more than 50 species, referred to the following genera: Anacardites, Anemia, Andromeda, Apeiobopsis, Apocynophyllum, Bambusa, Bumelia, Celastrus, Diospyros, Echitonium, Ficus, Flabellaria, Laurus, Lygodium, Morinda, Myrica, Myrsine, Nerium, Palmacites, Podocarpus, Quercus, Sabalites, and others.

The upper Eocene—Ludian, Priabonian, and Ligurian (if the last is made to include the "gypse," which by many students is placed in the lower Oligocene)—has a rich flora, that described by Saporta [6] from Aix in Provence, France, being the most complete and remarkable. It is much later in character than the Claiborne flora and need not be considered in detail. The floras from the lignites of Häring [7] in the Tyrol and from Monte Promina [8] and other localities in Dalmatia [9] belong at about this level or slightly higher.

In North America, on the border between the Cretaceous and the Eocene in the Rocky Mountain province, a large number of local floras appear. These floras are found in the Arapahoe and Denver formations of Colorado, the Livingston formation and the Lance formation ("Hell Creek beds") of Montana, the "Ceratops beds" (Lance formation) of Wyoming, and in various other areas. The deposits in which they occur consist of lacustrine, fluviatile, and terrestrial deposits derived from the rising land area of the Rocky Mountain province. Some are embraced in what Cross has termed the Shoshone group,[1] and the others are referred by Knowlton [2] to what he calls the lower member of the Fort Union formation. They may profitably be compared with the Paleocene of Europe. All were apparently laid down subsequent to the epeirogenic uplift which marks the close of the conformable Cretaceous deposits in this general region, or, in other words, are post-Laramie. Their floras are, according to F. H. Knowlton, markedly distinct from that of the true Laramie and are, on the other hand, essentially identical in character with the flora of the true Fort Union. These floral relations correspond to the conformable sequence by which the deposits pass into those of the typical Fort Union in some of the areas.

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[1] Heer, Oswald, On the fossil flora of Bovey Tracey: Philos. Trans. Roy. Soc. London, vol. 152B, 1862, pp. 1039–1086, Pls. LV LXXI.

[2] On the correlation of the Bournemouth marine series with the Bracklesham beds, the upper and middle Bagshot beds of the London basin and the Bovey Tracey beds: Geol. Mag., 1879, pp. 148–154.

[3] The lignite of Bovey Tracey: Philos. Trans. Roy. Soc. London, vol. 201B, 1910, pp. 161–178, Pls. XV–XVI.

[4] Essai descriptif sur les plantes fossiles des arkoses de Brives près le Puy-en-Velay, 1878.

[5] Annales sci. géol., vol. 9, 1877, pp. 1–72, Pls. VIII–XXII; Bull. Soc. Linn. Normandie (III), vol. 1, 1877, pp. 121–123; vol. 2, 1878, pp. 46–50; Compt. rend., vol. 92, 1881, p. 759; vol. 100, 1885, p. 870; vol. 103, 1886, pp. 487, 699, 894, 1143.

[6] Études sur la végétation du sud-est de la France à l'époque tertiaire: Ann. sci. nat., botanique, sér. 5, vol. 9, 1868, suppl. 1, Révision de la flore fossile des gypses d'Aix; sér. 7, vol. 7, 1888, Dernières adjonctions à la flore fossile d'Aix-en-Provence.

[7] Ettingshausen, Constantin, Abhandl. K.-k. geol. Reichsanstalt Wien, vol. 2, Abth. 3, 1853, pp. 1–118, Pls. I–XXXI.

[8] Ettingshausen, Constantin, Denkschr. K. Akad. Wiss. Wien, Math.-nat. Kl., vol. 8, 1854, pp. 17–44, Pls. I–XIV; Sitzungsber. K. Akad. Wiss. Wien, Math.-nat. Kl., vol. 12, 1854, pp. 180–182.

[9] Kerner, Fritz v., Tertiärpflanzen vom Ostrande des Sinjsko Polje in Dalmatien: Verhandl. K.-k. geol. Reichsanstalt, 1902, pp. 342–344.

Most known American Eocene floras, however, come from the basal Eocene or Fort Union formation, between 500 and 600 species having been collected from the beds of this age (Thanetian ?). This flora is apparently of northern origin and is very different in character from the Georgia Eocene flora. It is characterized by species of Aralia, Celastrus, Cocculus, Corylus, Elæodendron, Ficus, Ginkgo, Glyptostrobus, Grewiopsis, Hicoria, Juglans, Onoclea, Populus, Platanus, Pterospermites, Sapindus, Sequoia, Taxodium, Viburnum, and other genera, and presents everywhere an unmistakable botanical facies. Its marked contrast with the Claiborne flora of Georgia is to be explained in part by the fact that the one is a seacoast flora of tropical affinities, whereas the other is an inland flora, in the main of temperate affinities, although it contains palms, figs, camphor trees, and other warm-temperate types, indicating a climate moderately warm and humid, marked by mild winters but far from tropical. The Fort Union flora is, of course, a much older Eocene flora than that of the Claiborne of Georgia, which is more nearly the age of that of the Green River formation of Wyoming. Present knowledge of the flora of the Green River formation, with which the flora of the Florissant lake beds of Colorado was confused by Lesquereux, is due to the labors of Lesquereux [3] and Newberry.[4] As described by these authors, excluding that of the much younger Florissant lake beds, the Green River flora embraces the following number of species in the genera enumerated:

Acrostichum, 1.
Alnus, 1.
Ampelopsis, 1.
Aralia, 1.
Arundo, 2.
Brasenia?, 1.
Cheilanthes, 1.
Cissus, 1.
Cyperus, 1.
Equisetum, 1.
Eucalyptus?, 1.
Ficus, 4.
Ilex, 2.
Juglans, 3.
Leguminosites, 1.
Lygodium, 1.
Manicaria, 1.
Musophyllum, 1.
Myrica, 1.
Phragmites, 1.
Planera, 2.
Quercus, 2.
Rhus, 1.
Sabal, 1.
Salix, 2.
Sapindus, 1.
Sphæria, 1.
Zizyphus, 2.

This flora indicates a considerably warmer climate than that of the Fort Union, for it includes such types as Acrostichum, Manicaria, and Musophyllum. It furnishes points of contact with the Georgia Eocene flora in the species of Acrostichum, which is very close to the Georgia species, in an identical species of Arundo, and in the common generic representation of Ficus and Sapindus. It differs in the presence of genera like Ilex, Juglans, Myrica, Planera, Quercus, Rhus, Salix, and Zizyphus, which are for the most part temperate types.

The inland flora of the Georgia area contemporaneous with the Claiborne strand flora, if known, would undoubtedly furnish additional forms similar to those of the Green River formation, which show a commingling of warm temperate and tropical types such as are found in modern times in the subtropical and temperate rain forests with a mean annual temperature of about 14° C., uniform humidity, and a rainfall exceeding 200 centimeters per annum.

The Green River formation, on the evidence of its vertebrate remains, is correlated by Osborn [5] with the upper Ypresian of France, a correlation not very different from that indicated by the accompanying plant remains, which suggest a comparison with the more recent Lutetian stage of the Paris basin. The Green River is the only described middle Eocene flora known on this continent. Other Eocene floras deserving of mention in this connection are those of the Clarno formation in the John Day basin, Oreg., and the so-called "Eolignitic" flora (Wilcox and Midway groups) of the Mississippi embayment. The lower Clarno flora (Cherry Creek, Oreg.), is lower Eocene in age and includes the number of species indicated of the following genera:[1]

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[1] Cross, Whitman, Proc. Washington Acad. Sci., vol. 11, 1909, pp. 27–45.

[2] Knowlton, F. H., idem, pp. 179–238.

[3] Lesquereux, Leo, Cretaceous and Tertiary floras, 1883.

[4] Newberry, J. S., The later extinct floras of North America: Mon. U. S. Geol. Survey, vol. 35, 1898.

[5] Osborn, H. F., Age of mammals, 1910, p. 42.

Aralia, 2.
Asplenium, 1.
Cinnamomum, 1.
Cornus, 1.
Diospyros, 1.
Equisetum, 1.
Ficus, 1.
Hicoria, 1.
Juglans, 2.
Lastrea, 1.
Lygodium, 1.
Magnolia, 2.
Pteris, 1.
Quercus, 2.
Rhamnus, 1.
Salix, 1.

It has been compared by Knowlton with the upper Fort Union flora. The upper Clarno flora (Bridge Creek, etc., Oreg.) is of upper Eocene age and has been compared by Knowlton with the Green River flora. It includes the number of species indicated of the following genera:[2]

Acer, 2.
Alnus, 5.
Ailanthus, 1.
Betula, 4.
Berberis, 1.
Carpinus, 1.
Cassia, 1.
Corylus, 1.
Cratægus, 1.
Cinnamomum, 1.
Ficus, 1.
Fraxinus, 2.
Grewia, 2.
Hicoria, 1.
Juglans, 4.
Liquidambar, 1.
Myrica, 1.
Platanus, 2.
Quercus, 7.
Rhamnus, 1.
Sapindus, 1.
Sequoia, 2.
Ulmus, 2.

Neither of these John Day Eocene floras offers any points of resemblance to that of Georgia.

The "Eolignitic" flora of the Mississippi embayment for the most part has yet to be described. Many years ago Lesquereux[3] described various collections made in this area by Professor Hilgard, and Hollick[4] has described a small collection from Louisiana. There is a very large field for future work in this area, as Tertiary plants in a most excellent state of preservation are common at a considerable number of localities in Alabama, Mississippi, Arkansas, Tennessee, Kentucky, and Louisiana. All these described lower Eocene plants appear to be older than the Claiborne and merit a few comments. In Lesquereux's report such familiar genera as Populus, Salix, Quercus, Juglans, and Magnolia are discussed, but not all the identifications appear to be well founded. In the writer's judgment the Salisburia is a fern of the genus Lygodium, *Populus monodon* is not a Populus but a Ficus, and it is doubtful if *Salix worthenii* and *Salix tabellaris* are willows. *Quercus moorii* and the forms identified as *Quercus lyellii* Heer and *Quercus chlorophylla* Unger, the writer believes, are hardly oaks, and the latter of the three is suggestive of Rhizophora. The Banksia described by Lesquereux is not, in the writer's opinion, referable to that genus; and *Magnolia hilgardiana* and *Magnolia laurifolia* are both suggestive of Terminalia. Doubtless modern methods of collecting and study would result in a very different intrepretation of this flora and would furnish much data regarding physical conditions.

The writer spent parts of the field seasons of 1910–1913 in collecting in the embayment area. Very extensive collections were made, especially from the Wilcox group, and these collections are being elaborated at the present time. They fully confirm the above statements. These floras are subtropical in character and show many features similar to those of the early Tertiary floras of the south of England as elaborated by Ettingshausen.

The flora described by Hollick from Louisiana has nothing in common with that of Georgia, and the fossils might well have been compared with the existing arborescent flora of the American tropics rather than with fossil plants listed in previously published works. It is apparently a more tropical flora than that described by Lesquereux, for it contains, among other interesting things, at least two species of breadfruit (Artocarpus).

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[1] Knowlton, F. H., Bull. U. S. Geol. Survey No. 204, 1902.

[2] Knowlton, F. H., loc. cit.

[3] Lesquereux, Leo, Am. Jour. Sci., 2d ser., vol. 27, 1859, pp. 363–366; Proc. Am. Philos. Soc., new ser., vol. 13, 1869, pp. 411–430, Pls. XIV–XXII.

[4] Hollick, Arthur, in Harris, G. D., and Veatch, Otto, A preliminary report on the geology of Louisiana, 1900, pp. 276–288, Pls. XXXII–XLVIII.

Knowlton[1] has described a few fossil woods from Arkansas and has identified a small collection of leaf remains of Eocene age from Texas.[2] Penhallow[3] has also described some fossil woods from the Texas Eocene.

Other American Eocene floras deserving of mention are those of the Kenai formation of the north Pacific coast region.[4] They have nothing in common with the Claiborne flora and are said to be of upper Eocene age. A full historical sketch, with references to the older works and lists of the forms collected, is given in various papers by Knowlton.[5] Their chief interest rests on the fact that they are apparently of the same age as the widespread so-called "Arctic Miocene" of Heer. Another flora of upper Eocene age correlated with the upper Clarno flora of the John Day basin in Oregon is the meager one described by Knowlton from The Dalles, Oreg.,[6] and that of the Payette formation collected along Snake River in western Idaho.[7] These are all so far removed from the Georgia area and are also so much younger that they are of slight interest in the present connection.

In central Washington several Eocene formations have been described as containing fossil plants.[8] The oldest of these is the Swauk formation, outcropping just east of the Cascade Mountains. The flora, as yet undescribed, is said to be a representative one and is remarkable for its large and abundant palms and for the Central American and tropical South American types which it contains.

Separated from the Swauk formation by several hundred or thousand feet of basaltic lava flows and interbedded tuffs is the Roslyn formation bearing an Eocene flora of a more temperate type, apparently lacking palms and other tropical plants. A still younger Eocene formation is the Manastash formation, which contains a temperate flora as yet undescribed. There is also an extensive but undescribed Eocene flora in the Puget group of Washington west of the Cascade Mountains.[9]

ECOLOGIC CONDITIONS INDICATED BY THE BOTANIC CHARACTER OF THE FLORA.

The Georgia Claiborne flora is not extensive, as it embraces only 17 well-defined species, and these forms are not representative of the Claiborne flora as a whole but are for the most part representative of a single or at most two plant associations—one the strand flora, confined to the beach and extending inland where the edaphic factors were favorable, and the other the coastal swamp flora, more or less confined to muddy or possibly sandy shores between low and high tide.

These 17 species are distributed in fifteen families and include one fungus, one fern, and four Monocotyledonæ—a reed, a Potamogeton, a Pistia, and a palm. There are 11 Dicotyledonæ, representing the families Ulmaceæ, Fagaceæ, Moraceæ, Nyctaginaceæ, Mimosaceæ, Lauraceæ, Terminaliaceæ, Rhizophoraceæ, Dodonæaceæ, and Sapindaceæ. No gymnosperms, which are usually represented in European Lutetian floras, at least by the genus Podocarpus, have been discovered.[10] The following table of described species, all of which are new to science, gives in one column the described fossil species with which the Georgia plants are compared and in another the geologic occurrence or range of these species. A third column shows the existing species with which these Claiborne plants are most closely allied and a fourth column the geographic distribution and the character of the habitat of these species.

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[1] Knowlton, F. H., Ann. Rept. Geol. Survey Arkansas for 1889, 1890, vol. 2, pp. 249–267, Pls. IX–XI.

[2] Knowlton, F. H., in Vaughan, T. W., Am. Geologist, vol. 16, 1895, pp. 308, 309.

[3] Penhallow, D. P., Trans. Roy. Soc. Canada, 3d ser., vol. 1, sec. 4, 1908, pp. 93–113.

[4] This flora is being studied by Dr. Hollick.

[5] Knowlton, F. H., Harriman Alaska Expedition, vol. 4, 1904, pp. 149–162, Pls. XXII and XXIII; Bull. Geol. Soc. America, vol. 5, 1893, pp. 573–590; Proc. U. S. Nat. Mus., vol. 17, 1894, pp. 207–240, Pl. IX.

[6] Knowlton, F. H., Bull. U. S. Geol. Survey No. 204, 1902, p. 112.

[7] Knowlton, F. H., Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1898, pp. 721–744, Pls. XCIX–CII.

[8] Knowlton in Smith, G. O., Mount Stuart folio (No. 106), Geol. Atlas U. S., U. S. Geol. Survey, 1904, pp. 5 and 7.

[9] Knowlton, F. H., in Willis, Bailey, and Smith, G. O., Tacoma folio (No. 54), Geol. Atlas U. S., U. S. Geol. Survey, 1899, p. 3.

[10] The writer has recently found the genus Arthrotaxis, a coastal type, in the Eocene deposits of the Mississippi embayment.

Existing and fossil species comparable to the Claiborne flora of Georgia.

Georgia species.	Fossil species for comparison.	Range.	Living species for comparison.	Habitat and range.
Acrostichum georgianum	Acrostichum hesperium Newberry.	Green River	Acrostichum aureum Linné.	Swamps, Florida to Brazil, Africa, Asia, Polynesia, and Australia.
Arundo pseudogoepperti	Arundo goepperti (Münster) Heer.	Oligocene to Pliocene.	Arundo donax Linné	Wet places, Mediterranean region.
Castanea clairbornensis			Castanea dentata (Marsh) Borkhausen.	Uplands, Maine to Alabama.
Conocarpus eocenica	Eugenia aizoon Unger Eugenia hæringiana Unger	Oligocene	Conocarpus erectus Linné	Muddy or sandy shores, Florida to Galapagos Islands, west tropical Africa.
Dodonæa viscosoides	Dodonæa species of Europe.	Upper Eocene and Oligocene.	Dodonæa viscosa Linné	Florida keys and tropical shores of both hemispheres.
Ficus claibornensis	Ficus species	Eocene	Ficus sp	Beach jungle of tropical America.
Malapoenna sp			Malapœnna geniculata (Walt.) Coulter.	Shallow ponds, Georgia to Louisiana.
Momisia americana	Cinnamomum species	Eocene	Momisia aculeata (Swartz) Klatsch.	Florida keys and throughout tropical America.
Pisonia claibornensis	Pisonia eocenica Ettingshausen.	Ligurian	Pisonia macranthocarpa Donnell Smith.	Shore zone, Central America.
Pistia claibornensis			Pistia stratiotes Linné	Aquatic floating plant, tropics and subtropics of Old and New Worlds.
Potamogeton megaphyllus	Ottelia parisiensis Saporta	Lutetian		
Rhizophora eocenica			Rhizophora mangle Linné.	Tidal flats, American tropics and subtropics.
Sapindus georgiana	Sapindus affinis Newberry Sapindus angustifolius Lesquereux.	Mouth of Yellowstone. Lower Eocene of Gulf.	Sapindus saponaria Linné	Strand, Bermuda and Florida keys to South America.
Sphærites claibornensis	Sphærites myricæ (Lesq.) Mesch.	Green River	Various Pyrenomycetes	
Terminalia phæocarpoides	Terminalia radobojensis Unger.	Tongrian to Astian	Terminalia phæocarpa Eichler.	Strand, northern South America.
Thrinax eocenica	Flabellaria raphifolia (Sternberg) Ettingshausen.	Ligurian of Dalmatia.[a]	Thrinax sp	

[a] Not the other recorded occurrences.

Before considering the facts which may be legitimately deduced from this fossil flora it might be valuable to point out frankly to what extent the writer feels certain of his identifications. It is believed that all the identifications have been made with unusual care and that a considerably larger amount of comparative living material has been passed in review than is generally customary. The National Herbarium and the collection of the New York Botanical Garden have been carefully searched for modern analogues of these fossil leaves; the latter institution is especially rich in comparative material because it has been so active of late years in West Indian exploration. It is believed that the following genera are positively recognized: Acrostichum, Castanea, Dodonæa, Ficus, Conocarpus, Rhizophora, Pistia, Sapindus, Sphærites, and Thrinax. With regard to the genus Rhizophora, other tropical genera have somewhat similar coriaceous leaves, but the associated species in the Claiborne and the contemporary physical conditions serve firmly to corroborate this identification. Both Terminalia and Momisia are less certainly identified. They are types of leaves that might belong to other and unrelated genera; this is especially true of the Momisia, though both fossils agree remarkably well in their characters with the leaves of the recent species with which they have been compared and fossil leaves similar to those which have been here referred to Terminalia are elsewhere accompanied by characteristic fruits. The Pisonia agrees perfectly with the leaves of the existing species with which it has been compared, and is generically identical with other fossil leaves so identified. The reference of the Arundo to the grasses is positive, but in so far as its generic affinity is concerned the writer has simply conformed to paleobotanic usage. The form classed as Potamogeton may not be a Potamogeton, although it resembles that genus very closely and is most certainly a monocotyledon of aquatic or semiaquatic habit.

In examining these Claiborne forms and the ecology of the modern types with which they have been compared, it will be observed that only three species, the Castanea, the Pistia, and the Potamogeton, are not coastal forms, and that the two last-named forms are aquatics whose presence associated with coastal swamp or strand plants is not difficult to explain. The Castanea, then, apparently represents the only upland type preserved in this flora, and, as it is not common, the presumption is strong that it was brought down to the basin of sedimentation by some Eocene river, most likely by the river which it seems certain emptied into this Claiborne estuary.

It is interesting to note that the remaining 12 species are all plants of a coastal habitat, their modern representatives flourishing in tidal nipa swamps of the Orient, in mangrove swamps of the Orient and Occident, on the strand in beach jungle, or on the landward side of coastal sand dunes. Nearly all are represented by forms found in the existing flora on the Florida keys or along the shores of peninsular Florida, some, like the Conocarpus, flourishing equally well on either muddy or sandy shores. Every species has representatives in the American tropics, and four of the compared forms, *Conocarpus erectus*, *Dodonæa viscosa*, *Rhizophora mangle*, and *Sapindus saponaria*, range northward to Bermuda. In Schimper's classical work on the Indo-Malayan strand flora the following representation of species in genera which occur in the Claiborne flora may be noted:

Acrostichum (Chrysodium), 1 sp.
Dodonæa (viscosa), 1 sp.
Eugenia, 2 sp. (represented in West Africa and in America by the allied genus Conocarpus).
Ficus, 1 sp.
Malapoenna (Litsæa), 1 sp.
Pisonia, 4 sp.
Rhizophora, 2 sp.
Sapindus, 1 sp.
Terminalia, 1 sp. (catappa).

Of these the Sapindus, Terminalia, Dodonæa, Ficus, Malapoenna, and Pisonia are more particularly elements in the littoral forest (beach jungle of Kurz, Barringtonia formation of Schimper); the others are integral members of or rather intimately associated with the Rhizophora or Nipa associations. It is really remarkable to what an extent the identified elements in the Claiborne flora of Georgia agree in indicating the character of their habitats, which were tidal Rhizophora swamps at certain points in the Grovetown estuary where the conditions were favorable, and elsewhere the sand beaches or the rain forests, which, if they did not come down to the water's edge, were developed behind the dunes that possibly in places formed the highest inner margin of the beach.

The Claiborne species of Conocarpus, Dodonæa, Ficus, Pisonia, Rhizophora, Sapindus, and Terminalia all have more or less coriaceous leaves, due to a combination of factors of which the following may be enumerated. Those which grew below the level of high tide had to withstand the salinity of the estuary waters and those which grew above high tide in more or less exposed situations had to withstand the drying effect of windblown salt spray, which must have been considerable and which undoubtedly was an important factor, just as it is in similarly situated plant associations in the existing flora. Another factor was the strong light of low latitudes, to which was added reflection from the water in the mangrove swamps and from the sand in the beach jungles.

Certain deductions regarding the climate and rainfall of the latitude of Grovetown in Claiborne time can be drawn from the distribution of the modern allies of these fossil forms. Since they are all rather uniform in their distribution, the accompanying sketch map (fig. 11) showing the geographic range of the modern species of Rhizophora will serve in a measure for all the genera.

The present winter isotherm in the latitude of Grovetown is approximately 48° F. None of the closely allied modern plants flourish north of the winter isotherm of 52° F. and most of them do not occur north of the winter isotherm of 60° F. None of the fossil forms except possibly the Potamogeton, the modern species of which range over a great many degrees of latitude, or the Castanea, which likewise has a wide range, would be expected to occur outside the latitudes where what Schimper calls the subtropical or warm temperate rain forests are found. We would expect the Claiborne climate, at least at low elevations along the coast and in proximity to the warm Eocene ocean current or currents, to have been uniformly humid, with an annual rainfall somewhere between 150 and 200 centimeters. The actual rainfall could become a more or less negligible factor provided the water table approached close to the surface and the humidity was high and constant. The temperature would have to be uniform rather than hot, judging by modern standards, for any degree of winter cold would have been fatal. This climate need not have been tropical, nor would it be surprising if the Claiborne marine fauna failed to show tropical forms or reef corals, for the main factors which would limit the spread of a flora like the one described would be uniform humidity, ample rainfall, and the absence of severe cold. In the existing flora these favorable factors permit the existence of an almost tropical plant growth in New Zealand uplands, in latitude 40° south, and a quasi-tropical vegetation might flourish much more readily in latitude 33° north in Eocene time, particularly along a coast. Minimum temperatures mark the limits of distribution; other factors, such as soil, humidity, and rainfall, furnish optimum conditions for development within these wider limits.[1]

Such considerations are in a large measure corroborated by the results of investigations of the conditions in Europe at this time. It is well known that the middle Eocene floras of Europe show many tropical characters absent in the lower Eocene. These characters first become marked in the fruits from the London clays and the leaves from Alum Bay and in homotaxial deposits on the Continent, and though it was formerly the common practice to correlate these floras with Australian or African types, they show closer affinities with the modern floras of Malaysia and tropical America, as was long ago suggested by Gardner. The sketch map forming figure 12 (p. 160) will bring this out very well. It shows the distribution of the modern genus Nipa and of the Eocene genus Nipadites, which is indistinguishable from the modern Nipa. Nipa has only one existing species, which inhabits the tidal waters of the Indian Ocean and ranges from India through the Malay Archipelago to the Philippines, vying with the mangroves for possession of the tidal flats. It produces clusters of large floating fruits, and similar fruits form the basis for the genus Nipadites. As shown by the map, these tropical or subtropical floras ranged northward in Europe at this time to southern England or, on this continent, to about the latitude of Newfoundland. These Eocene Nipa swamps furnished a congenial habitat for a species of Acrostichum closely allied to the one described from the Georgia Claiborne, and other comparable forms are not wanting. A species of Pandanus is associated with Nipadites in the Paris basin just as the two are found associated at the present time in the Oriental tropics, and many similar occurrences could be mentioned.

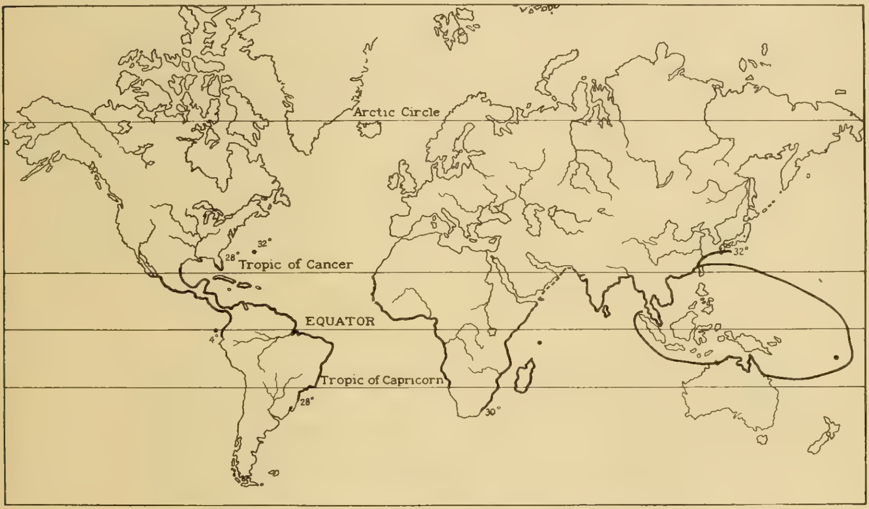

FIGURE 11.—Sketch map showing the distribution of existing species of Rhizophora.

The Lutetian abroad and the Claiborne in this country are both characterized by a considerable transgression of the sea.

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[1] The real factor recognized in the foregoing statement is not so much killing cold as length of growing season.

As the Claiborne flora of Georgia indicates more tropical conditions than the known earlier Eocene floras, it seems probable that its direction of advance was from the tropics northward. The Claiborne strand flora was so largely dependent upon warm ocean currents for its dispersal and survival that an Eocene representative of the Gulf Stream can be safely assumed. Even if the course of this current was offshore, the coastal area was under its direct influence by reason of accessory or counter currents of similar character. Tidal currents more or less transverse to the shore line and minor wind-blown currents assisted in carrying the oceanic drift into the shallows and through the inlets into the estuaries, or over the sand bars into the lagoons. Judging from modern conditions in comparable areas the general direction of the prevailing winds was either parallel with or transverse to the coast line, and though considerable minor variations probably existed, their general direction was probably from the southeast during the greater part of the year.

In studying the present flora the writer became much interested in the means of dissemination of its modern allies. It has been shown that certain species of Eugenia, Terminalia, Rhizophora, Pisonia, and Sapindus have become adapted for dispersal through the agency of ocean currents by specialization of their fruits or seeds, which have developed air chambers or woody husks for buoyancy and practically impervious coverings to exclude sea water from their vital parts. Best known, perhaps, is the extreme specialization of the mangrove, which sends its germinating plantlets out into the world fully prepared to anchor themselves in water of the required depth. The somewhat similar specialization of the other members of this flora, though less in degree, is almost as effective, judging by the geographic distribution of these genera in the existing flora, so that the part played by ocean currents is considerable, despite the contrary opinion of De Candolle. Hemsley has even recorded seeds of such a plant as *Sapindus saponaria* washing ashore on the south coast of Bermuda and actually germinating; in fact, this author gives a large amount of interesting data upon the dispersal of plants by ocean currents in his discussion of insular floras in the *Challenger* report devoted to such floras. Other species of the Georgia Claiborne flora, particularly species of Ficus, may be supposed to have been distributed by fruit-eating birds; in fact, the seeds of a number of modern species of Ficus have been recorded from the crops of birds. The same means of distribution may

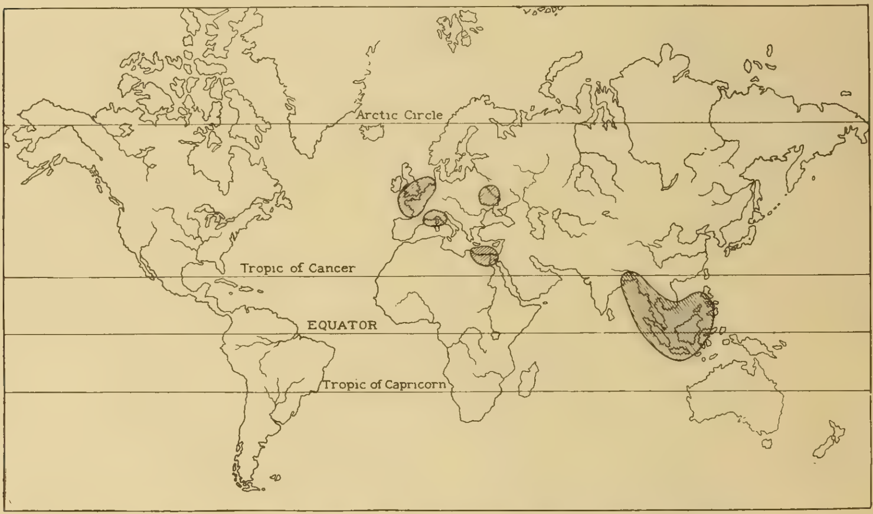
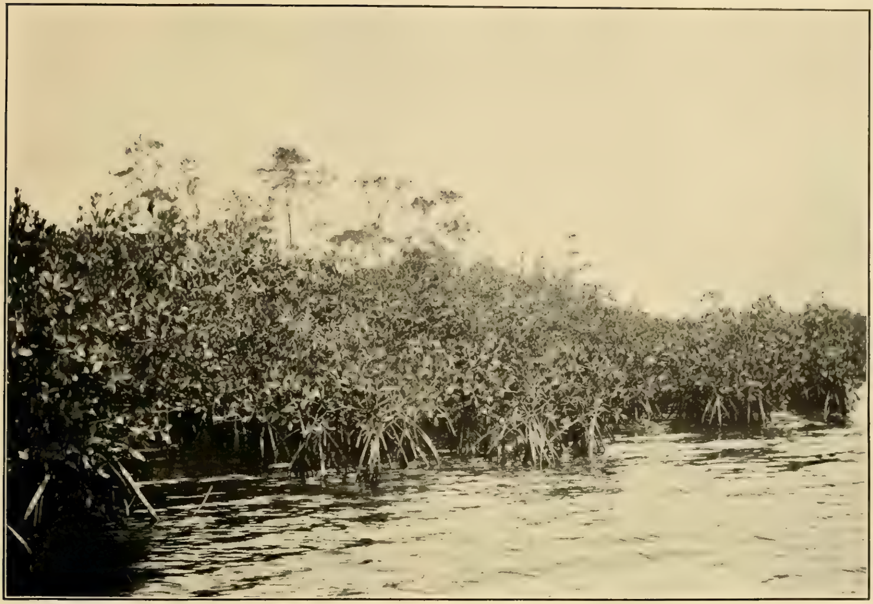
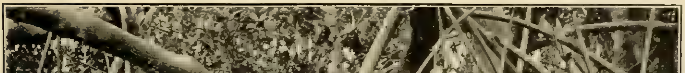


FIGURE 12.—Sketch map showing the distribution of Nipa (northwest-southeast ruling) and Nipadites (northeast-southwest ruling).



A. MANGROVE SWAMP ALONG MIAMI RIVER, NEAR MIAMI, FLA.



B. HABIT OF GROWTH OF MANGROVES ALONG MIAMI RIVER.

have been also applied to the Malapoenna, but no data concerning methods of distribution are available for the small remainder of the Claiborne forms.

It can be readily shown that the existing flora of peninsular Florida, the Bahamas, and Bermuda contains a large element which has been derived in comparatively recent geologic times from the south. Almost the entire flora of the Bahamas and Bermuda has had such an origin. If, however, geographic distribution is studied in the light of historical geology, the main elements in these modern floras will be found to have been already in existence in the middle Eocene, if not earlier. Such study shows that nearly all the modern plant families, except possibly the most specialized forms, as the orchids among the Monocotyledonæ or the Compositæ and their allies among the Dicotyledonæ, were at some period more widely distributed than they are at the present time, and that the details of modern distribution represent not so much the interchange of different types between continents as the greater or less degree of segregation of descendants of forms once spread over much wider areas. This generalization is made even more emphatic when the comparisons embrace the floras of the Upper Cretaceous, although the certainty of identification based upon foliar characters for many genera varies more or less directly with the length of time that they have been preserved.

From a study of the Claiborne flora it is evident that the main elements of the modern flora of tropical America reached at least as far north as latitude 33° and probably several degrees farther in the middle Eocene, and that in post-Eocene time, probably not until toward the close of the Tertiary, they retreated southward to the West Indies, Central America, and northern South America as the result of lowering temperatures or diminished rainfall or both. Therefore, though the strictly modern movement of the subtropical flora along the course of the Gulf Stream has been from the south toward the north as the various coral islands of the Bahamas formed, this dispersion was preceded by similar migrations on a much more extended scale during the early Tertiary. From a study of the marine faunas of Florida Dall[1] places this change of climate at the close of the Oligocene and predicates[2] a southwardly flowing cold ocean current to account for it.

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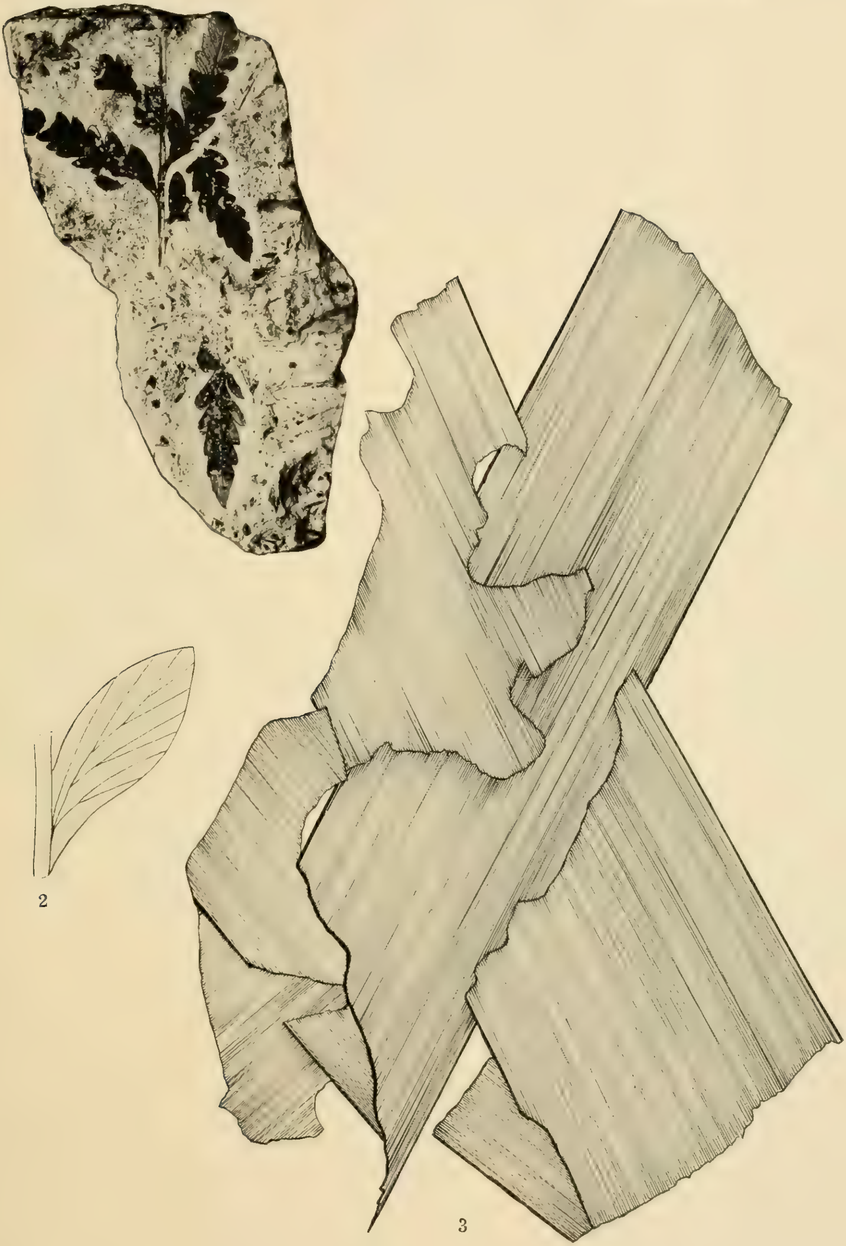
FIGURES 1, 2. *Dryopterites stephensoni* Berry 103
    1. Type found near Byron.
    2. Pinnule of same, × 6.

FIGURE 3. *Doryanthites cretacea* Berry (type, found near Buena Vista) 108

All the specimens are from the Eutaw formation.



UPPER CRETACEOUS PLANTS FROM GEORGIA.

PLATE XVIII.

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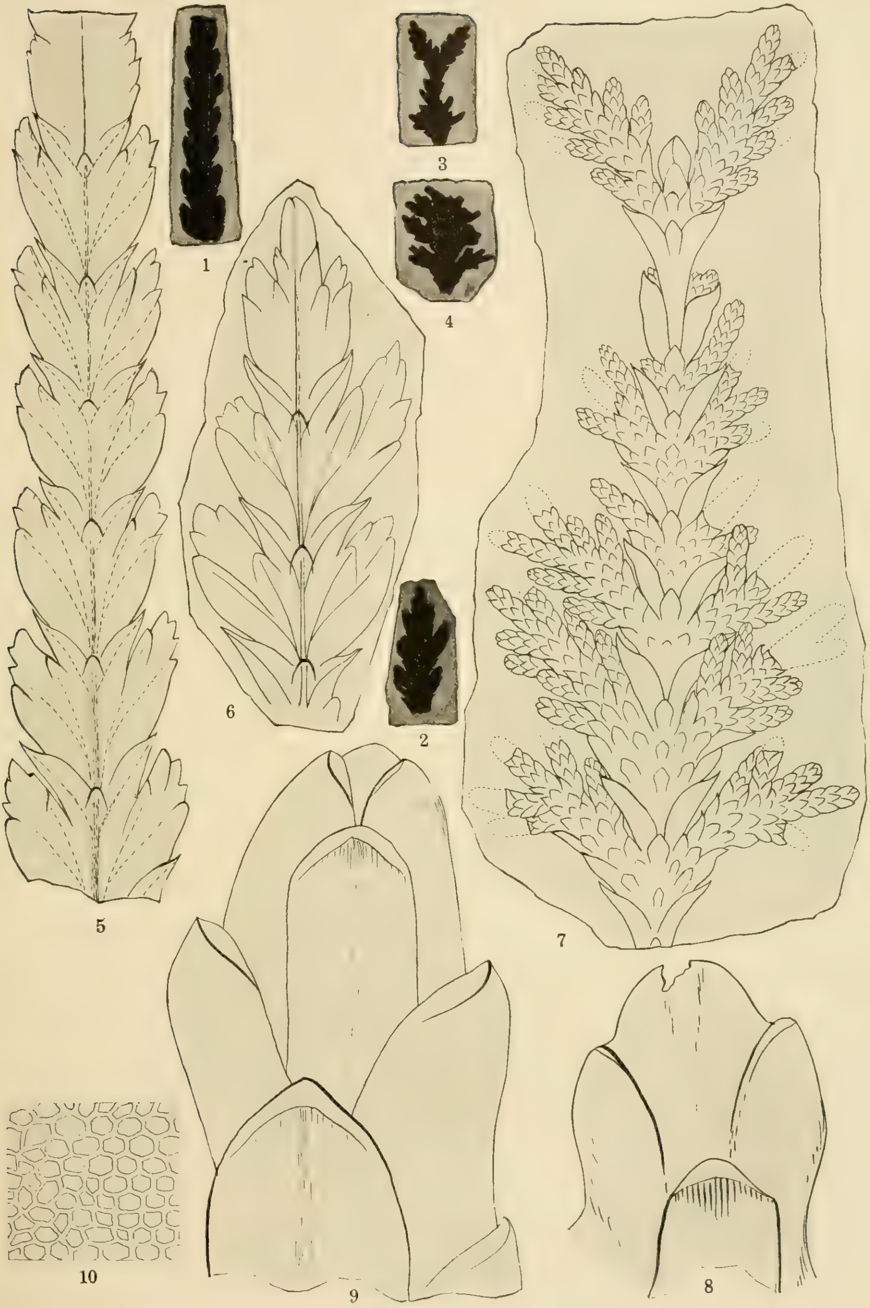
1–4. Specimens, natural size, from McBrides Ford.
5–7. Same, × 4.
8, 9. Apical part of two lateral twigs, × 45.
10. Epidermis, × 205.

All the specimens are from the Eutaw formation.



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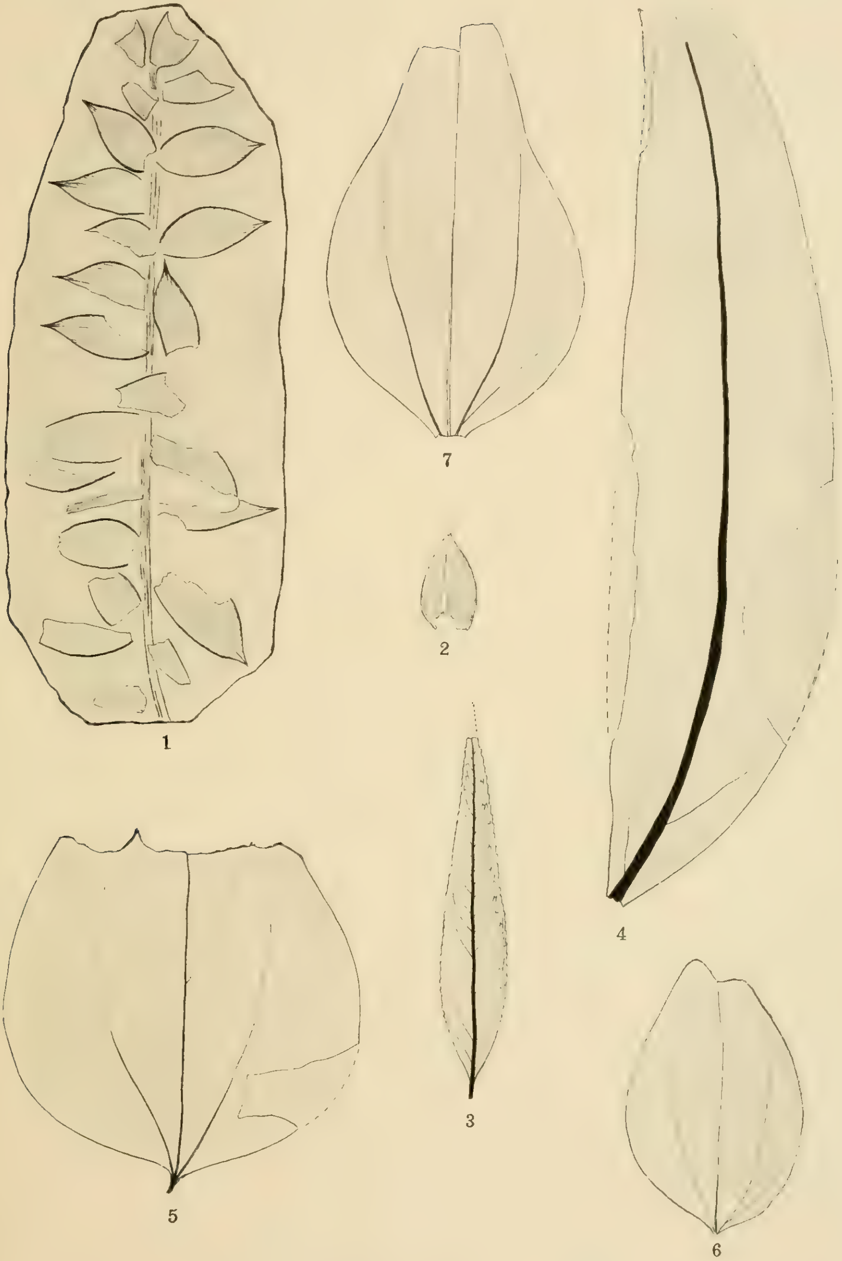
1. Figure of a specimen from Horrell Landing, N. C., to illustrate the method of occurrence at Chimney Bluff, Ga.
2. Method of occurrence near Buena Vista.

FIGURE 3. *Salix eutawensis* Berry, the most complete specimen from Broken Arrow Bend 109

FIGURE 4. *Ficus krausiana* Heer, Chimney Bluff 110

FIGURES 5–7. *Ficus ovatifolia* Berry, McBrides Ford 111

All the specimens are from the Eutaw formation.



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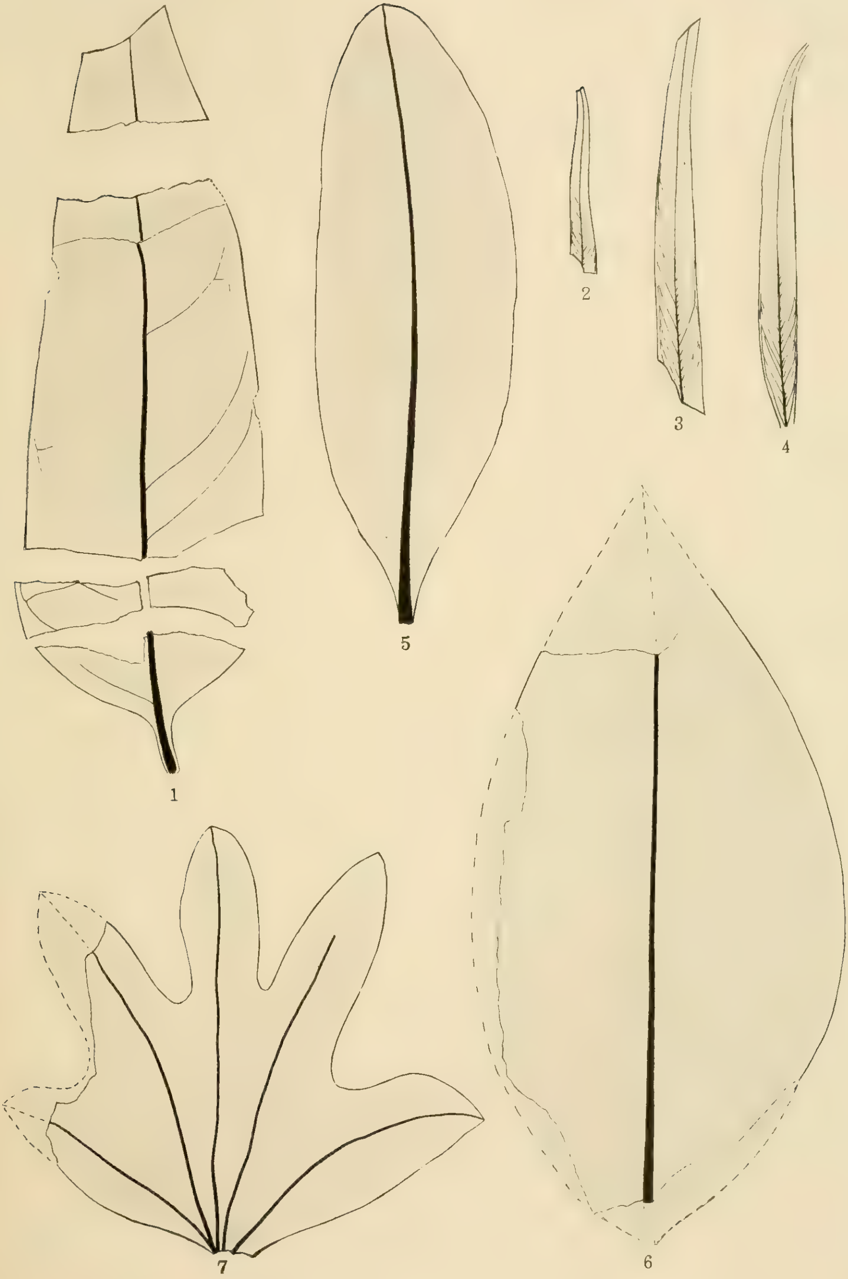
All the specimens are from the Eutaw formation.



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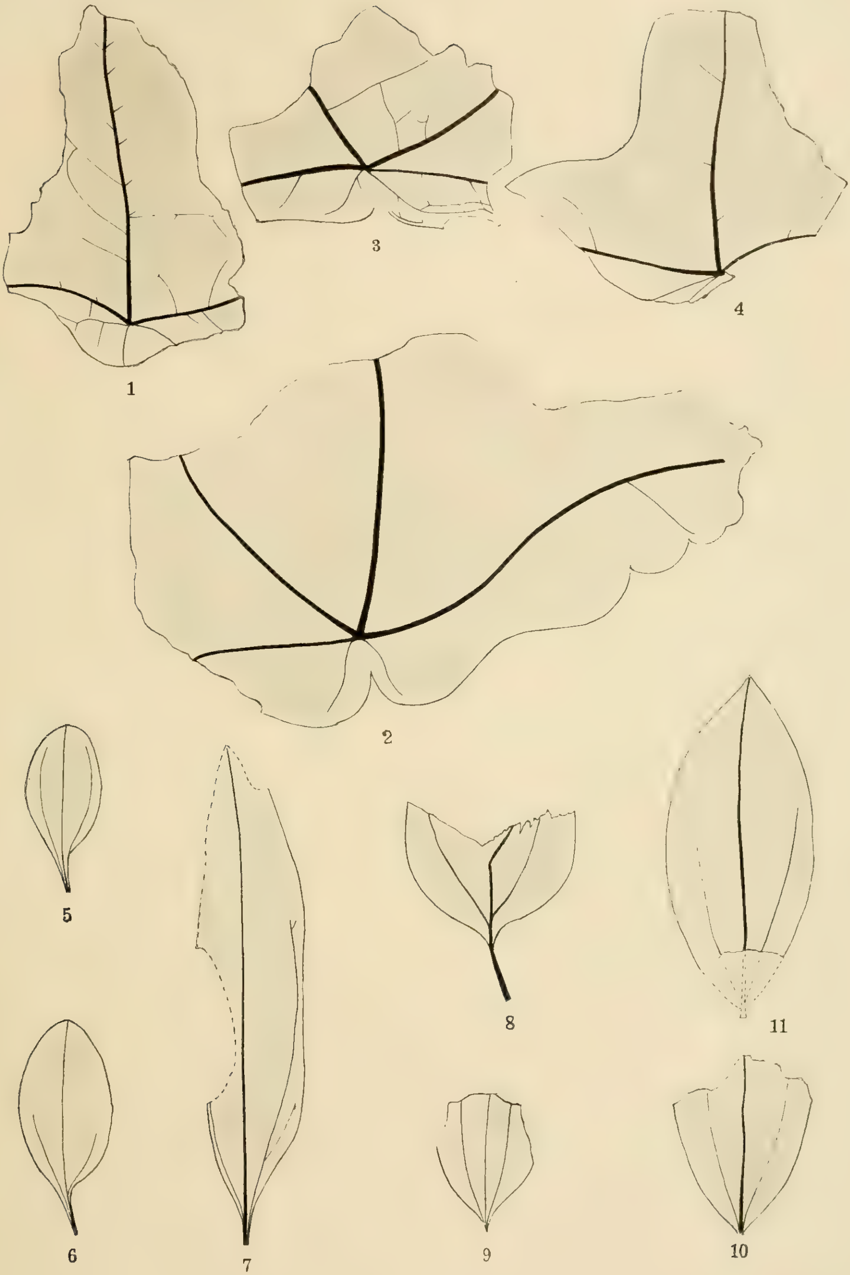
All the specimens are from the Eutaw formation.



UPPER CRETACEOUS PLANTS FROM GEORGIA.

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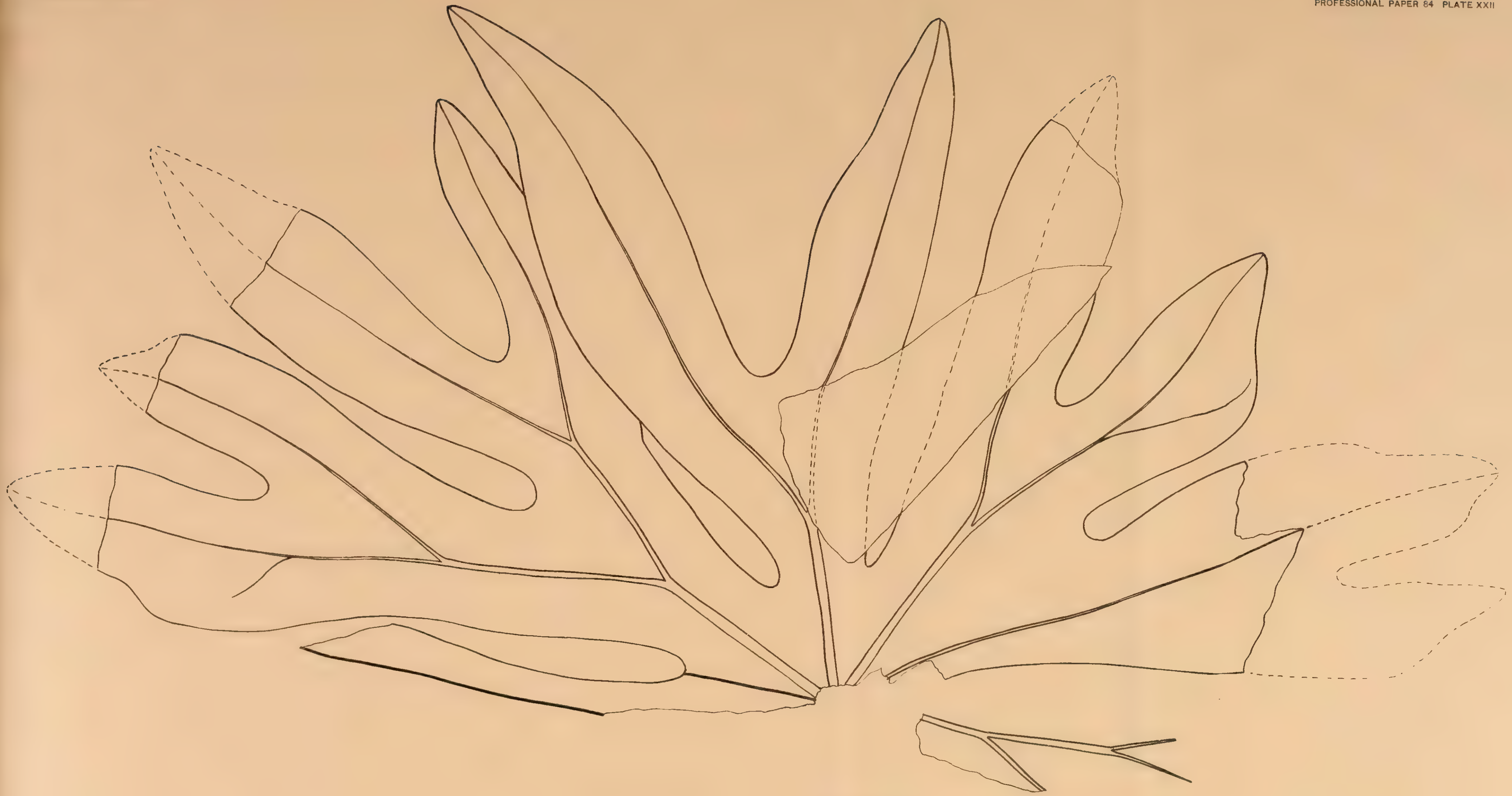

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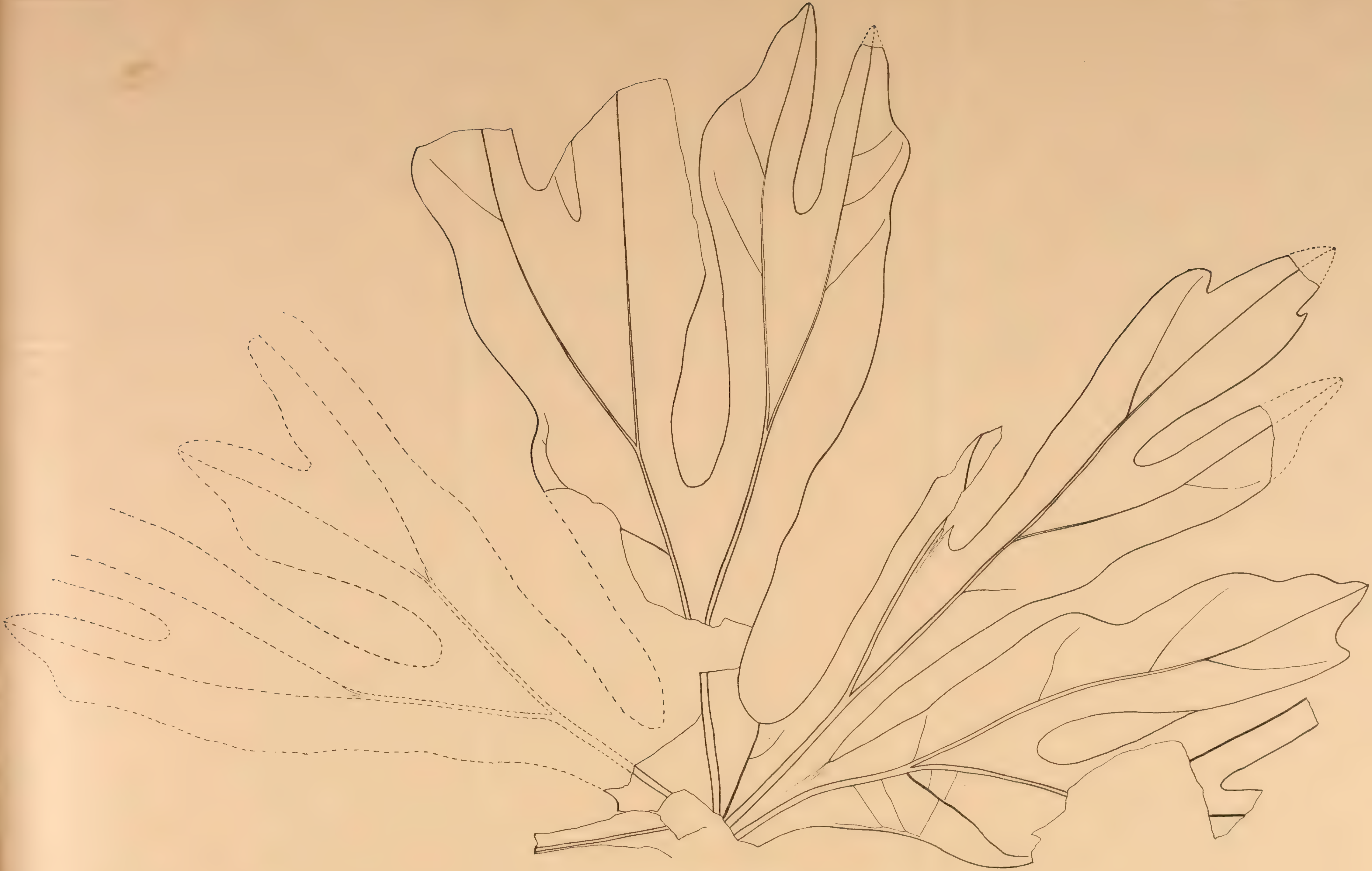

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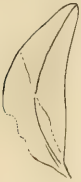
All the specimens except those shown in figures 6 and 7 are from the Eutaw formation. The specimens shown in figures 6 and 7 are from the Congaree clay member of the McBean formation.



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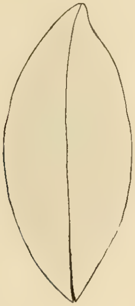

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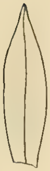

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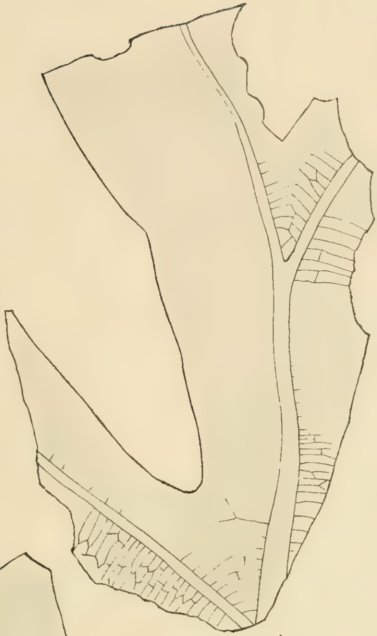

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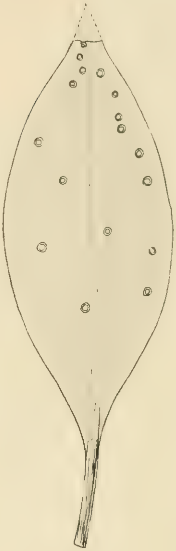

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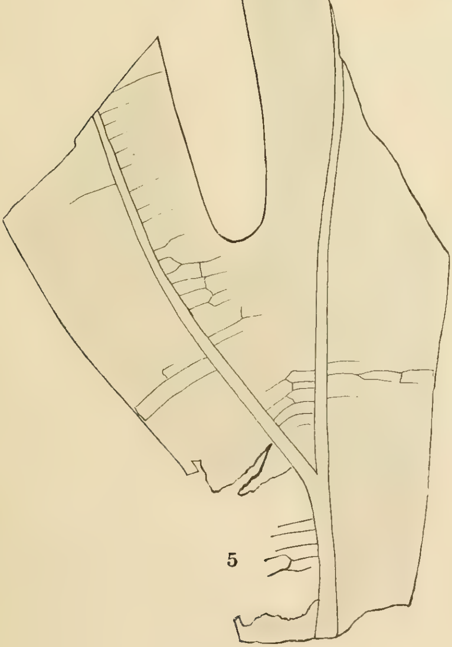

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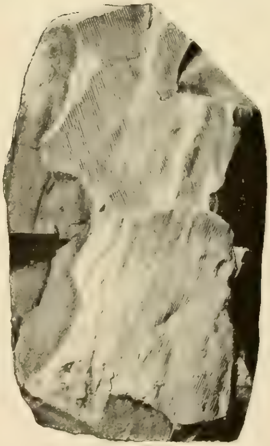

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UPPER CRETACEOUS AND EOCENE PLANTS FROM GEORGIA.

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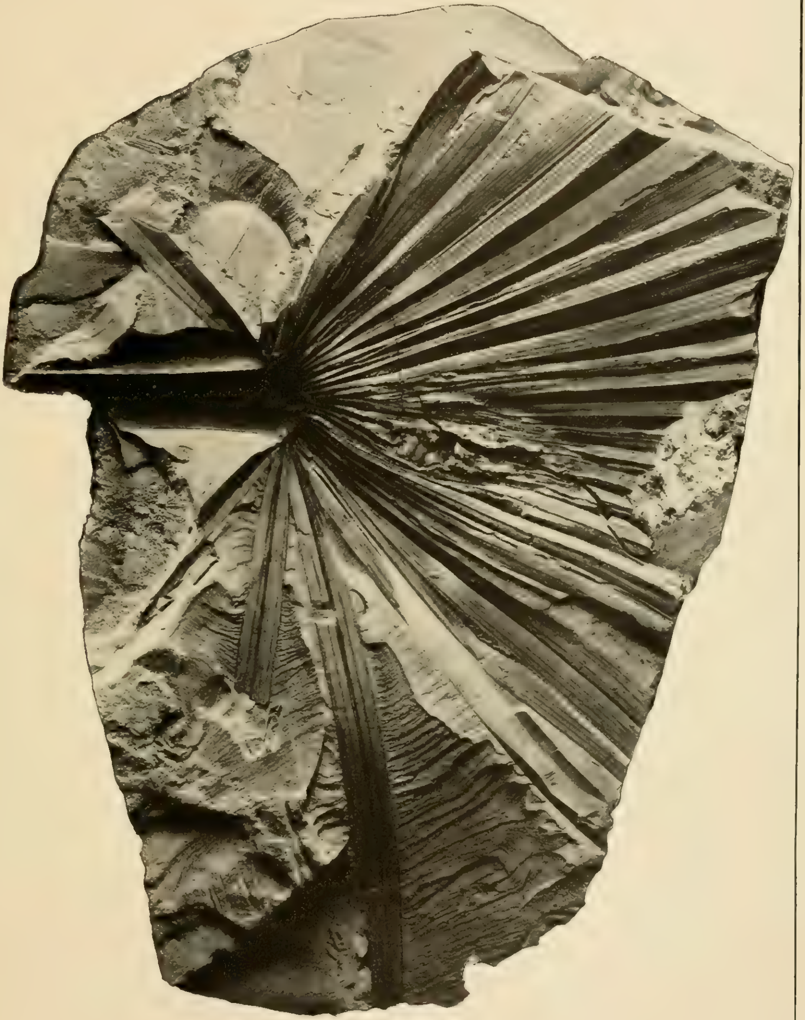

EOCENE PLANT FROM GEORGIA.

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2. Same, showing traces of venation.

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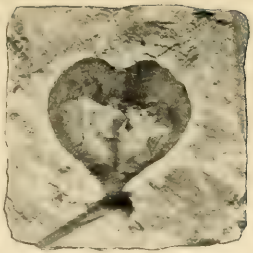
All the specimens are from the Congaree clay member of the McBean formation.



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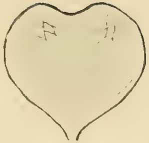

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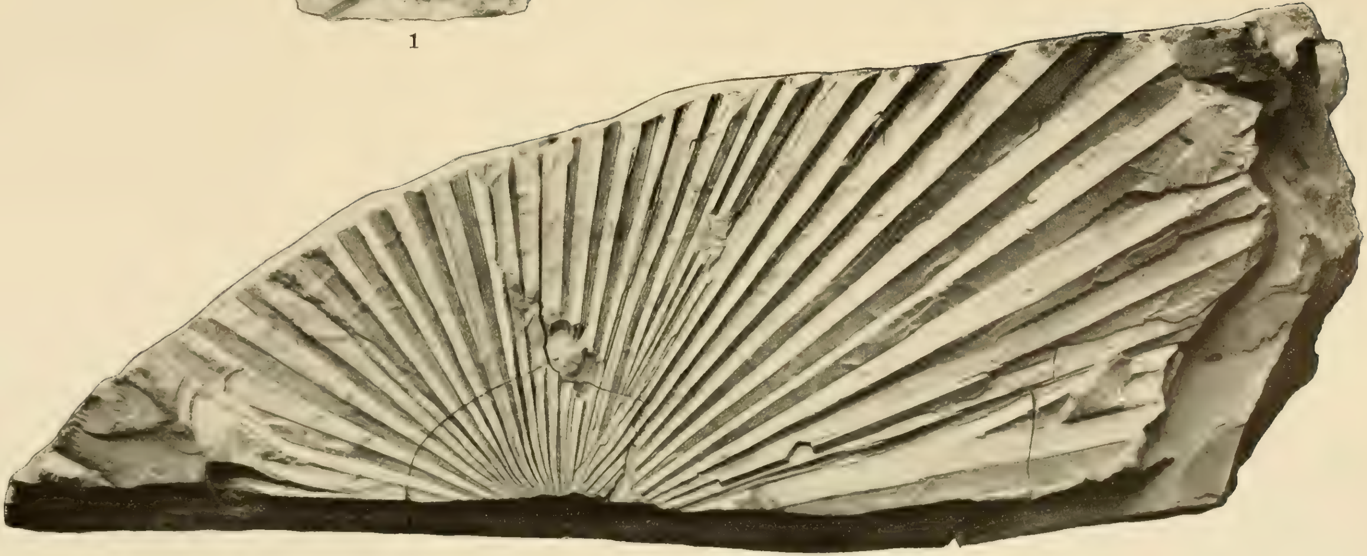

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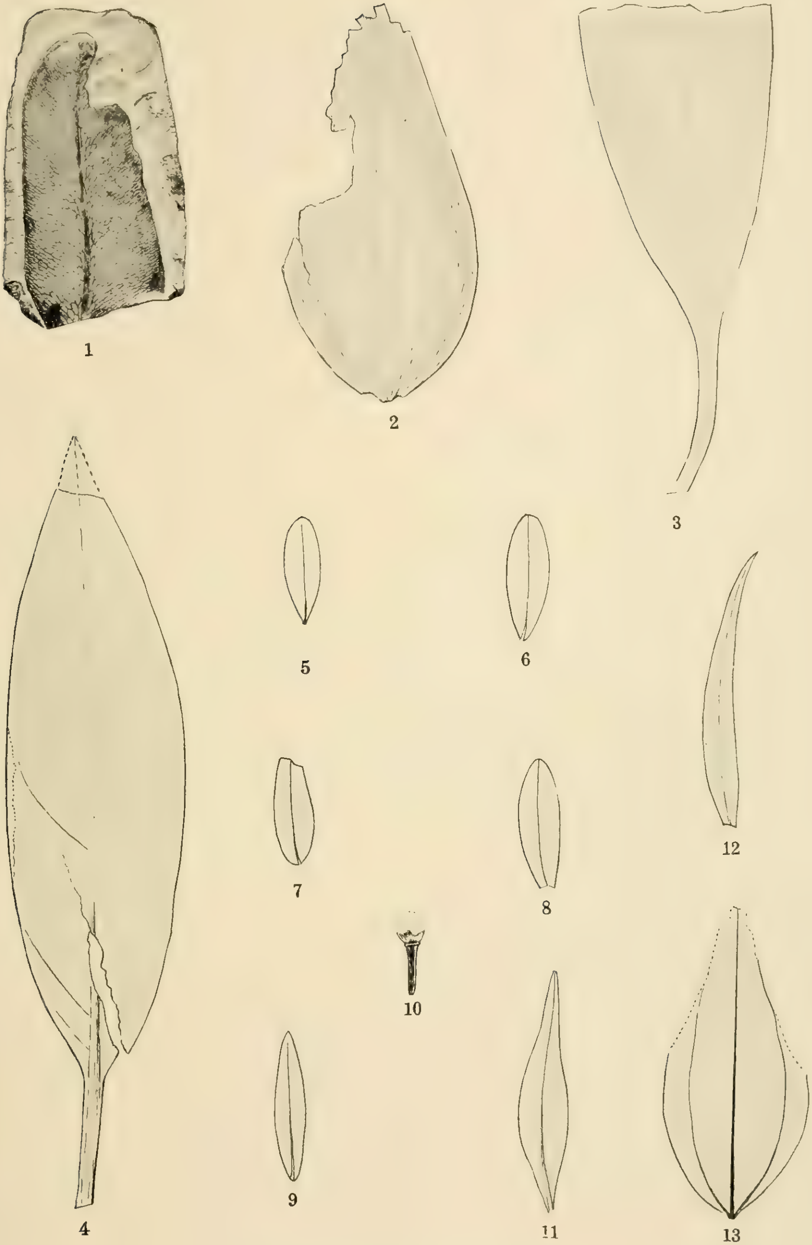
All the specimens are from the Congaree clay member of the McBean formation.



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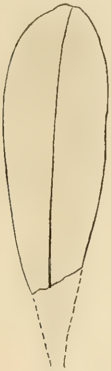
All the specimens are from the Congaree clay member of the McBean formation.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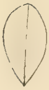
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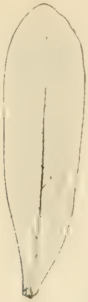
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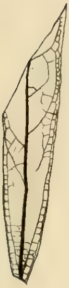
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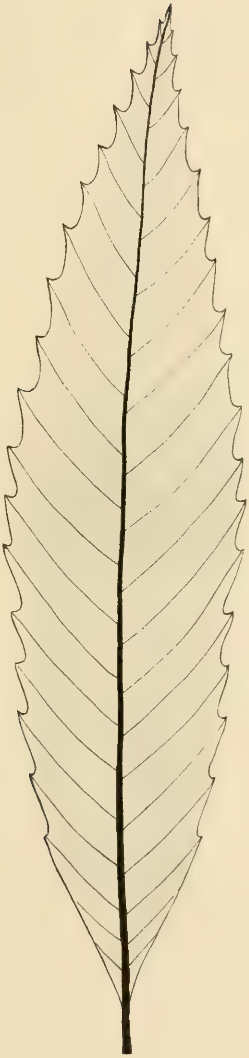
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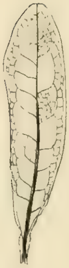
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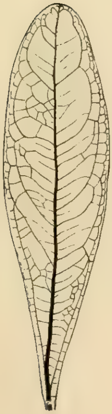
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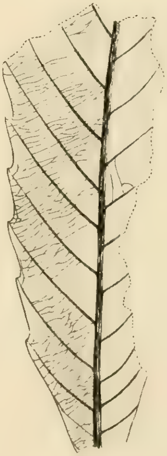
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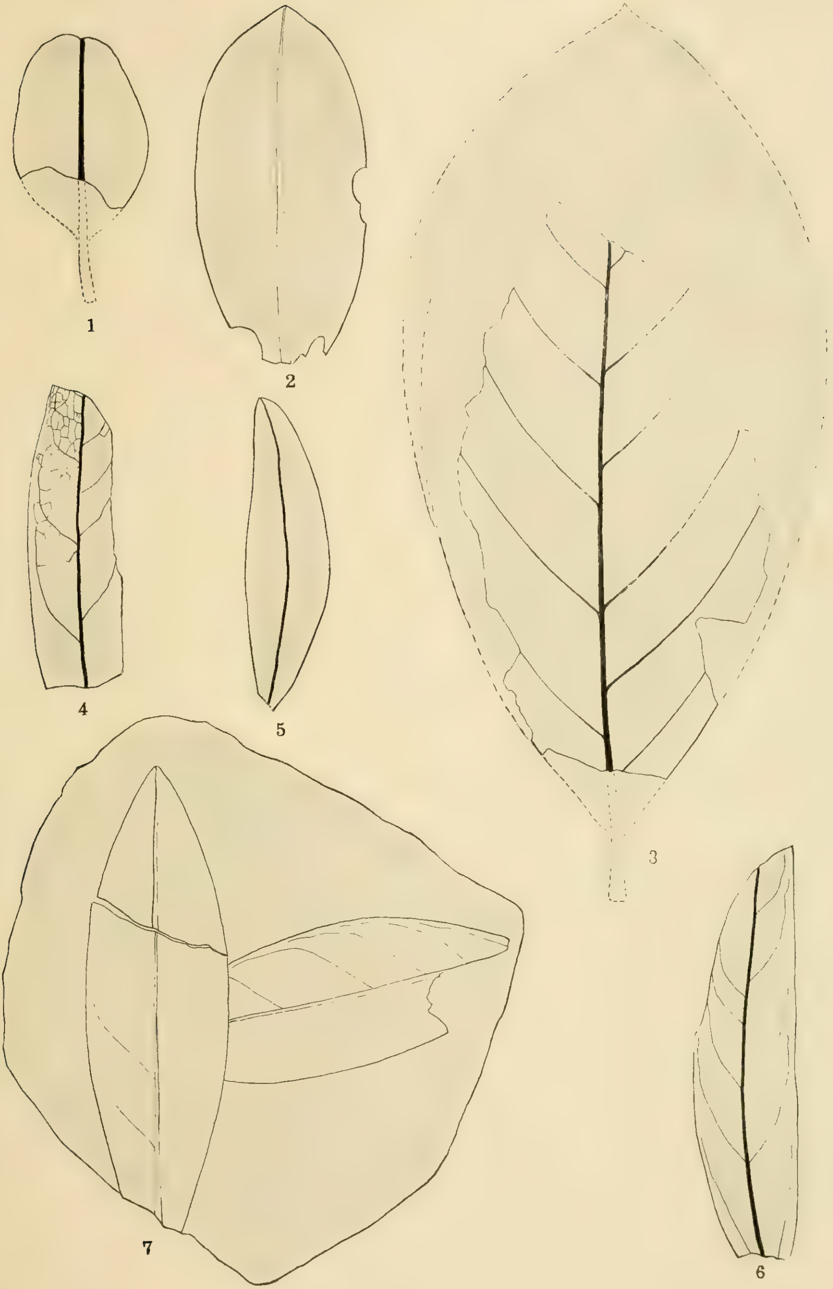
All the specimens are from the Congaree clay member of the McBean formation.



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1913

DAVID WHITE, Chief Geologist

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PREFACE.

The present paper is the first of a new series to be published by the Geological Survey under the title "Shorter contributions to general geology." Of late years Survey authors have become contributors to scientific and technical journals to an extent that suggests the need of an official channel for papers of a certain type. Contribution to these outside journals is a valuable phase of the Survey's activity and will continue; but this method of publication has certain limitations by reason of both the capacity and the circulation of these journals. The time has come for beginning a volume that will afford opportunity for the publication of short papers and preliminary reports of a character not well adapted to publication in any of the forms heretofore used by the Survey.

It is significant that so many of the Survey geologists are making scientific contributions of general interest that represent results incidental to other investigations or that are of the nature of by-products of work whose immediate purpose is economic. This is because the so-called economic work of the Survey is really scientific. It is scientific in method and scientific in results. It represents the application of science to the solution of problems whose main bearing may be utilitarian but which, if successfully solved, will afford by-products in results and principles that will yield greater ultimate possibilities of use to man. In order to encourage greater breadth of observation and investigation among the geologists and to promote the scientific possibilities of their professional work, means should be provided for prompt publication of such papers in a permanent form that will commend itself to both author and reader. Provision has been made since 1902 for the current publication of short papers relating specifically to economic geology, and the new series here established is intended to make similar provision for scientific papers relating to general geology.

In advance of the printing of the full volume, separates, each including one or more papers, will be issued to the number of 10 or 12 a year as the manuscript and illustrations are ready, without waiting for material for the full volume to be in hand or even promised. These separates will be paged continuously, so that the volume will be simply a consolidation of the separates, without change of pagination, a distinct advantage for bibliographic reference. The date of publication will be printed on the title-page of each separate.

The papers included in these "Shorter contributions to general geology" may relate to any phase of geology, provided it possesses general interest—petrology, paleontology, stratigraphy, glaciology, structural geology, etc. This volume is intended not as a catch-all for current odds and ends, but as a dignified collection of scientific contributions, each suitable in importance of subject, value of results, and quality of treatment for separate publication as a bulletin or professional paper if it were of sufficient length.

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY, 1913.

THE ORIGIN OF COLEMANITE DEPOSITS.

By Hoyt S. Gale.

INTRODUCTION.

A brief study of several of the more important borate deposits in southern California during 1912 has suggested to the writer some ideas believed to be new regarding the origin of colemanite. The theory presented here has not yet been entirely proved, but as there is much in its favor and as it affords suggestions and a working basis for further observation, which the writer also hopes to have opportunity to make, it seems proper to place the matter briefly on record.

This paper is based chiefly on a short personal study of the borate deposits in Ventura County, Cal., supplemented by more cursory examinations of similar deposits in the vicinity of Death Valley, and includes a review of published data on this subject and of personal communications from those who have visited deposits elsewhere. A report discussing the economic geology of the colemanite deposits of Ventura County and the mining operations on them will appear in another place.[1] It is believed that these deposits afford exceptional opportunities for the study of the relationships of the colemanite ores.

VOLCANIC ORIGIN OF BORIC ACID.

It is generally recognized that boric acid in considerable quantities is an original constituent in the waters and gases given off with volcanic emanations. In fact, the Tuscan fumaroles have been an important commercial source of boric acid in Italy for a long time, and in the past, possibly even to the present time, almost all the boric acid brought into the European market was derived from this source. There is abundant evidence of the presence of boric acid in volcanic emanations in many parts of the world. On the other hand, boron is so rare a constituent of rock-forming minerals that it forms an almost inappreciably small percentage of the earth's rock mass as a whole. It is therefore natural in studying the genesis of boron minerals or deposits to look primarily for evidence of a possible origin in volcanic emanations. Such an origin is believed to be in fact strongly indicated by the relations to be observed in most borate deposits that have been studied.

HYPOTHESES REGARDING ORIGIN OF COLEMANITE.

The immediate origin of the colemanite ores of the southern part of the Great Basin has been discussed by several writers and geologists. W. H. Storms was perhaps the first to provide the explanation which has been more or less fully accepted since. In describing the deposits at Calico, near Daggett, Cal., he says:[2]

> To me it seems that what is now one of the most valuable deposits of mineral in the State was at one time the site of a Tertiary lake of considerable but as yet undetermined size; that although subjected to the same oscillation as the remainder of the region, a basin formed, in which the waters collected, carrying with them the mineral salts derived

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[1] Gale, Hoyt S., The borate deposits of Ventura County, Cal.: U. S. Geol. Survey Bull. 540-O, 1913.

[2] Storms, W. H., Mineral resources of San Bernardino County, Cal.: California State Min. Bur. Eleventh Ann. Rept., p. 346, 1893.

> from the rocks of the neighboring country; that finally the climatic conditions became such that the supply of water was less than the loss by absorption and evaporation, and the waters of the lake slowly diminished, it finally disappearing entirely, leaving on the floor of the lake a thick deposit of calcium borate of snowy whiteness.
>
> After the deposition of the borax bed a general subsidence of the region occurred, the waters of the great Tertiary lake once more covering the whole country. Again the sands and finer sedimentary material—the erosion of the mountains—were carried down and found a resting place on the floor of the lake, the borax beds being finally covered.

Subsequent deformation of these strata has tilted and erosion exposed the borate beds.

Campbell[1] adopted a similar explanation of the genesis of the deposits at the same locality:

> The borax of Death Valley, as well as that near Daggett, occurs in a regular stratum, interbedded with the semi-indurated sands and clays that make up the bulk of the strata. These beds are generally regarded as of Tertiary age, and they are supposed to have been deposited in inclosed bodies of water.
>
> * * * * * * * * *
>
> The principal deposit of boron salts [near Daggett] occurs at Borate, about 12 miles north of Daggett, in the vicinity of the old Calico mining district. The mineral found here is borate of lime, or colemanite, and it occurs as a bedded deposit from 5 to 30 feet in thickness, interstratified in lake sediments.

Spurr,[2] in discussing the character and formation of the Tertiary lake beds, says, with special reference to the borate of lime deposits: "The internal evidence of these beds shows that much of the material was laid down in inclosed lake basins, and that the colemanite beds are probably the result of the evaporation of Tertiary alkaline lakes during periods of aridity."

Later Keyes[3] suggested a modification of the hypothesis by assuming the Tertiary water bodies to have been marine, "a great shallow arm of the Pacific Ocean that had been cut off by the upheaval of the mountain ranges along the coast." As the fossils obtained from the sedimentary beds associated with the borates, at least in the Mohave Desert, indicate a land and fresh-water fauna exclusively, this modification of the hypothesis may probably be dismissed.

Baker[4] discusses at some length the character of the sediments associated with the borate deposits and refers to the genesis of borate ores near Daggett:

> The interbedded layers of colemanite, gypsum, and limestone were most probably deposited on the evaporation of a body of water of considerable depth, since the colemanite layer is from 5 to 30 feet in thickness. Layers of pure gypsum several inches thick are found, as well as more considerable thicknesses of what is probably chemically deposited limestone. An alternative hypothesis, that these minerals had their immediate origin in hot springs and solfataras opening directly into shallow lakes, perhaps only of seasonal duration, or in playas, has much to commend it, especially when considered in connection with the numerous evidences of shallow-water deposition. These evidences comprise ripple marks, sun cracks, rain prints, found on the finer as well as the coarser beds, and the layers of fine breccia and conglomerates interbedded with the fine shales and tuffs. Shallow lakes or ponds probably existed at times during the deposition of the fossiliferous tuff member, for they seem to be necessary to account for the presence of the gastropods. The paucity or absence of fossils in the borate and the fine ashy and shaly tuff members (but one specimen of a Planorbis was found in these beds), as well as the presence of the colemanite, limestone, and gypsum layers, apparently indicates the salinity of the waters. * * * Colemanite, gypsum, and limestone were deposited either by hot springs or solfataras in saline lakes, which might have been of shallow depth, or, having leached from the surrounding rocks, were precipitated during a time or times of evaporation of a former fresh-water lake of considerable depth.

Lately Eakle[5] has described the colemanite mined at Lang and summarized the origin of the deposit as follows:

> The bedded character of the deposit is evidence that the mineral crystallized from an evaporating solution, and that precipitations of both the borate and some of the silt which formed the shales took place. The solution filled a closed basin as a lake or marsh, probably similar to the alkali marshes of the desert regions. It is generally characteristic of such deposits that salts of various kinds, often in alternating series, especially carbonates and sulphates of lime and soda, make up the deposit, and the well-known Searles borax lake in San Bernardino County, with its many associated minerals, is a good illustration of a desert formation. The Lang deposit, however, is an exception, as the neocolemanite is practically unaccompanied by other minerals, except howlite, which is a silico-colemanite, and some calcite. Waters emptying into the basin could not have been charged with mixed alkali salts.
>
> It seems probable that the original site of the deposit was a marsh containing marl and calc tufa with mud and considerable organic growth, and that later waters charged with boracic acid flowed into the basin and converted the

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[1] Campbell, M. R., Reconnaissance of the borax deposits of Death Valley and Mohave Desert: U. S. Geol. Survey Bull. 200, pp. 8, 12, 1902.

[2] Spurr, J. E., Ore deposits of the Silver Peak quadrangle, Nevada: U. S. Geol. Survey Prof. Paper 55, p. 21, 1906.

[3] Keyes, C. R., Borax deposits of the United States: Am. Inst. Min. Eng. Bull. 34, 1909.

[4] Baker, C. L., Cenozoic history of the Mohave Desert: Univ. California Dept. Geology Bull., vol. 6, No. 15, 1911.

[5] Eakle, A. S., Neo-colemanite, a variety of colemanite, and howlite from Lang, Los Angeles County, Cal.: Univ. California Dept. Geology Bull., vol. 6, No. 9, 1911, pp. 179–189.

carbonate of lime into the borate. Some and perhaps the greater part of the argillaceous material which forms the shales was precipitated by the decomposition of the impure limestone, together with organic matter. The carbon dioxide set free may not wholly have escaped, but possibly became occluded in the mud and later converted into carbon. Most of the borate is of a blackish-gray color, due to impregnations of carbon along the cleavages and fractures. The conversion of the limestone into the borate in all probability took place before the overlying sandstones were formed. The absence of soda compounds and the presence of abundant plant life indicate that the lake or marsh was fresh, into which springs containing boric acid discharged. The deposit later became submerged and the sandstones were laid down.

The origin of the boric acid is presumably volcanic and the springs probably issued from vents in the immediate vicinity of the basin. The deposit is situated in a hilly district and is partly surrounded by high masses of volcanic tuffs and rhyolites. The subsequent tilting of the deposit was not accompanied by heat or pressure sufficient to modify the borate materially, yet the mineral shows lines of strain and columnar partings due to pressure and shrinkage. The fissile shales owe their solidity to this slight pressure, and carbonization to some extent was also the result. There is, of course, the possibility that all of the carbon in the deposit is from organic matter, the CO_2 of the carbonate escaping, as some of the shales are quite bituminous.

Eakle does not mention any immediate relation of the deposit to lavas, such as are known to be intimately associated with borate-bearing beds elsewhere, although he notes that the Lang district is partly surrounded by high masses of volcanic tuffs and rhyolites.

Study of the colemanite deposits in Ventura County, Cal., and observations on similar deposits near Death Valley have led the writer to the conclusion that these borate minerals and probably also most of the gypsum associated with them are vein deposits and not the product of evaporated lake waters. The evidence supporting this conclusion is set forth briefly below.

COLEMANITE DEPOSITS OF VENTURA COUNTY, CAL.

The Ventura County deposits of colemanite lie on the southern flank of Mount Pinos, near the San Emigdio Range, at the south end of the San Joaquin Valley. The colemanite is found within a series of bedded rock formations, which have been extensively folded and faulted. In general the trend of their outcrop is northeast and southwest, and the dip southeastward, away from the higher elevations of the Mount Pinos Range.

The section of sedimentary beds and lava with which the colemanite is associated is in general terms as follows:

Section of formations in which colemanite occurs in Ventura County, Cal.

Top of section measured.	Feet.
Shale and some sandstone	300
Basaltic lava flows, with intercalated layers or lenses of shale and limestone	600
Shale	600
Conglomerate, bowlders, or cobbles of light granitic rock cemented	600
Other sedimentary rocks below.	

These beds are believed to be of Miocene age. The more extensive stratigraphic section exposed in this general region has not been included here, as its possible relation to the borate ores seems remote and it evidently involves many complex problems. The beds defined above are apparently conformable. The most valuable borate deposits are included within the layers of shale and limestone intercalated within the flows of basalt, but borates occur also in the shales above and below the basaltic flow rock, though invariably in close association with this lava.

The following interpretation may be placed on the section given above. The base of the section is a massive conglomerate made up of bowlders or more or less rounded cobbles, in part very firmly cemented together, and the whole mass constitutes a rather distinct formational unit. This is supposed to be a piedmont alluvial deposit that was originally spread out from the base of the Mount Pinos Range. The core of the range is believed to be mainly granite of the character represented by the bowlders of this formation. The bowlders are coarser near the mountains and seem to grade off to finer material at greater distance, the formation as a whole taking on the character of sandstone, as illustrated at the Ives camp, at the lower end of the Middle Fork canyon. There seems little evidence in this formation to indicate other than subaerial distribution of very coarse detrital material. However, in the opinion of R. W. Pack, who has studied the areal geology of the north slope of the San Emigdio Range, there may exist some room for doubt that the coarse gravels were deposited subaerially. On the north slope of that range about 10 miles north of the borax mines he has found coarse conglomerate beds containing granitic bowlders several feet in diameter interstratified with fine sandstones and sandy and diatomaceous shales, the latter containing marine fossils of Miocene age. The coarse beds occur at several horizons and are so intimately associated with the fossiliferous strata as to suggest that the whole section is marine.

The shale overlying the bowlder conglomerate and sandstone is light-colored detrital material, thin bedded, and so readily eroded that it does not form conspicuous exposures. It has not been examined in detail, but it is supposed to be made up of muds derived by the more complete comminution of granitic material similar to the granite in composition. It may be a delta plain or alluvial deposit distributed by quieter waters than those which carried out the bowlder wash, or it may have been deposited under water. At present there is no conclusive evidence as to its origin.

Overlying the shale is a massive accumulation of flows of basaltic lava, with vesicular and slaggy layers. Evidently many distinct flows are represented in the thickness of some 600 feet measured on North Fork. These flows include several intercalated layers of shale and limestone, with which the most valuable colemanite deposits of the district are associated.

The basalt is overlain by another mass of shale and sandstone similar to that which underlies it. The history represented by these beds may be much like that which preceded the outpourings of the lava.

The colemanite of Ventura County is evidently typical of the mineral as it occurs elsewhere. It is found in solid crystalline masses of large size but of very irregular form. The mineral itself in its purest form is milky white, even glassy in part, much resembling pure-white calcite in general appearance and cleavage. The crystal forms are, however, quite distinct from those of calcite. The less pure massive ore includes grayish or even black crystalline bodies, the color of which is supposed to be due to included impurity.

The mineral masses as a whole are of very irregular form, but they have been generally described as bedded deposits, for they appear to follow the bedding of the sedimentary strata with which they are associated. When examined in detail, however, the mineral colemanite does not exhibit any bedding structure but only the forms characteristic of the crystallization of the mineral itself. The massive deposits are either crystalline without definite arrangement or show radial structures as well as seams of definitely vein-banded material, included between walls, in places containing open cavities lined with crystal terminations. The irregularity or bunchy character of the deposits alone would prohibit strict parallelism with the distinctly bedded shales in which they are included. Other evidence afforded by the deposits themselves is suggestive of formation in veins, as will be pointed out.

The larger deposits of colemanite, such as those of the Columbus, Russell, and Frazier mines, are associated with shale and limestone lenses included within the section of basalt lava flows. In each of the mines mentioned the colemanite ore appears to have been developed in immediate association with a bed of limestone included within the shale. This limestone is massive or of rough, porous character on the weathered outcrop, suggesting the designation "travertine-like." Basaltic lava occurs stratigraphically above and below the ore bodies and is generally encountered in the mine workings not far from the ore. The shale bands intercalated within the basalt flows much resemble the shales that both overlie and underlie the whole sequence of flows.

The present attitude of the beds that include the ore bodies ranges from nearly flat to steeply dipping. The nearly horizontal ore bodies in the Frazier mine are the development of beds near the crest of an anticlinal fold. In general the rocks dip steeply.

In one large deposit examined underground (in the Russell mine) the main ore body follows a zone of slip faulting, which is also approximately parallel to the bedding, the ore being limited with much distinctness by a wall of slickensided gouge.

The outcrops have rarely shown any colemanite, even in the ore-bearing zone. The one exception noted, that of the original discovery at the Frazier mine, was an exposure near the top of a very steep bluff in which a great amount of slipping had taken place and normal outcrops were not present. Possibly a minor amount of the borate minerals is also present elsewhere in the outcropping strata, but it is very inconspicuous and was not observed. As a rule the outcrop of the borate-bearing beds is either folded and crumpled shale or shale including a massive limestone ledge, the limestone forming the most conspicuous part of the outcrop. These zones are generally indicated by an abundance of gypsum, which is a marker followed in prospecting and occurs in the form of thin stringers included in the opened bedding planes and in cross fractures of the shale. All the gypsum is of the clear crystalline variety selenite, and no massive bedded deposits of gypsum are known in this region. The outcrops of these gypsiferous shales are also characteristically marked by the occurrence of "button" concretions—flattened spheroidal nodules or disks of calcareous composition that have very commonly been mistaken for fossils. The occurrence of these concretions at the outcrop of the basaltic lava, in the immediate vicinity of the ore-bearing zones, usually only a few feet distant, is believed to be significant and is generally noted and referred to by the prospector. As a rule, however, the prospector regards the lava as an intrusive "porphyry," which it clearly is not, as attested by its common vesicular and amygdaloidal character, as well as its distinctly bedded structure, conformable with the sedimentary strata.

Certain specimens collected on the ore dumps and in the mines show that at least a part of the colemanite is a replacement deposit. Irregular portions of the limestone are surrounded by white crystalline colemanite, and minute fractures which traverse the limestone throughout are also filled with this mineral. These veinlets are observed to have been enlarged irregularly within the limestone. Small rounded masses of limestone are also included within the solid portions of the colemanite, indicating that in places the same enlargement of intersecting veinlets has been carried to a further stage and the separated limestone portions are residual within the deposited colemanite.

GENERAL EVIDENCE OF VEIN CHARACTER OF COLEMANITE DEPOSITS.

The direct evidence of the character of the colemanite, of course, lies in the deposits themselves. If the deposits are of vein form, the evidence suggesting it has hitherto been overlooked. In natural outcrops relationships are obscure. The study of the ore in place is not facilitated by conditions at the mines. The old mining entries on the Ventura County deposits were, when visited, either inaccessible or, if open, were heavily timbered, dripping with water, and coated with mud, so that they were not favorable to detailed study of the character of the ore. The facts of observation therefore are not yet to be considered conclusive, and judgment as to whether these deposits originated as veins or through desiccation involves a study of other more general considerations.

Colemanite, the borate of lime, is relatively insoluble in water. A recent determination, made at the writer's suggestion by W. B. Hicks in the Geological Survey laboratory, of the solubility of certain specimens of apparently pure colemanite from the Ventura County deposits has shown that at ordinary temperatures (20° to 25° C.) about 1 part is soluble in about 1,100 parts of water. Van 't Hoff has shown that colemanite may be produced artificially by reactions from other calcium borates in saturated alkali chloride solutions, but the writer knows of no data concerning the possible formation of this mineral by direct reaction of boric acid and limestone. It is natural to assume that free boric acid, which is a common constituent of the later volcanic emanations in this general region, might react with limestone, and that by the substitution of boric for carbonic acid the lime borate would be formed. Thus by a process of metasomatic replacement might have been formed deposits of the typical irregular character of the known colemanite masses, roughly following the bedding of the original calcareous rock or of the interbedded lenticular bodies of limestone. Therefore in so far as the natural reactions are concerned the formation of colemanite as fissure and replacement vein deposits is well within the limits of possibility. But for other reasons also it seems that these colemanite deposits are not logically to be ascribed to deposition as the principal constituent of a residue derived from the waters of a desiccating saline lake.

Borates have been shown to exist in natural saline waters and desiccation deposits in many parts of the Great Basin and the desert country of the western United States. So far as known to the writer, however, colemanite has nowhere been deposited as a result of desiccation, but rather the boric acid has combined to form the more common surface saline minerals, such as ulexite and tincal. Is it therefore reasonable to suppose that ulexite, tincal, etc., could have been the primary deposits of such Tertiary dry-lake formations, from which colemanite had subsequently formed as a secondary product? If this had been so, would not some evidence of the primary deposit be at hand, either in the composition or in the structure of some parts of the colemanite deposits? Such evidence has not been recorded.

If colemanite were but a part of a natural saline residue deposited by the desiccation of the waters in which these materials had accumulated and become concentrated, it would be most natural to expect other salines that are commonly more abundant than the salts of boric acid in the typical desiccation deposits of the desert region. No appreciable amount of bedded salt, sodium sulphate, or carbonate is to be found with the colemanite deposits known to the writer. The borate-bearing shales of the Ventura County deposits are not even of a character that might be described as "alkaline" in ordinary desert parlance.

Gypsum and limestone, the latter travertine-like, occur in association with the borates, and former writings have already been quoted to the effect that both are chemical residues derived from the same desiccation that crystallized the colemanite. The gypsum associated with the borate-bearing shales is crystalline selenite. All or the greater part of it occurs in thin stringers, which not only follow the bedding joints of the shales but fill transverse fractures. The cross-fiber structure of much of this selenite is evidence of its deposition in veins. No rock gypsum of distinctively sedimentary character was observed in any of these beds. Gypsum is being deposited from ground waters along the walls of the mining entries at the present time. It still remains to be proved, therefore, that any gypsum of original sedimentary character is included with the borate-bearing deposits. All of this mineral present may have been introduced in solution by percolating ground waters. The stringers of gypsum noted so abundantly in the outcrops of the borate-bearing shales have not been shown to persist in like quantity in the few deeper developments of the mining entries.

The limestone strata with which the principal colemanite ore bodies are associated are evidently original in the sedimentary sequence. They are in part at least travertine-like, weathering in rough tufa-like surfaces, and are not compact like more typical limestones. Their character suggests the probability that they are chemical deposits, possibly of local extent, laid down in shallow waters, being similar to the travertine deposits now forming near springs or where ground waters flow into ponds or saline lakes. The limestone masses are believed to be of lenticular form and to occur interbedded with shales at various horizons within the flows of basaltic lava. They are not necessarily the product of desiccation.

In fact, there is little evidence from the stratigraphic section associated with the borate beds of Ventura County that can be taken to indicate the extensive lacustral conditions commonly assumed to have existed during the Miocene epoch in the Tertiary. Some of the associated deposits may have been "lake beds," but the writer believes rather that the submergences were the result of local, temporary, and variable conditions, such as may have occurred during or after periods of shallow flooding in the lower portions of piedmont fluviatile plains.

Lastly, an explanation of the source of the boric acid is to be sought. Naturally, a volcanic origin is suggested, and in Ventura County the association of the colemanite with the basaltic lava is certainly intimate. It is a common saying among prospectors of the district that "borax" will not be found except near a "porphyry contact" and in association with limestone. It is true that the larger ore bodies mined are all in close relation with some part of the basaltic lava flow rock in place, generally within a few feet of it. The borate-bearing beds follow the outcrop of the basalt flows throughout the district. The question in what way boric acid originating with the extrusion of these flows could have caused reactions and mineral deposition soon or long after the period of the lava extrusion remains for further investigation.

SUMMARY.

The evidence favoring the hypothesis of a desiccated saline lake to explain the origin of the colemanite has little to support it beyond rather general assumptions. The actual character of the deposits themselves indicates rather a vein type of formation. The gypsum which has been pointed to as a desiccation deposit related to the colemanite is also of vein character. Other salines which would naturally be expected in desiccation deposits resulting from natural saline solutions are not found in association with the colemanite. Those who have supported the desiccation hypothesis have offered no explanation of the reaction which might produce colemanite in such massive deposits as a product of water evaporation, while, on the contrary, its formation from limestone in veins by replacement of carbonic acid with boric acid is a natural working hypothesis that deserves experimental investigation. The relations of the deposits to basalt lava flows indicate the probable origin of the boric acid at the time of the extrusion of these lavas, although it may also be necessary to assume that this acid continued to find its way into solution of the circulating ground waters long after the period of the lava extrusions.

THE MUD LUMPS AT THE MOUTHS OF THE MISSISSIPPI.

By Eugene Wesley Shaw.

INTRODUCTION.

The territory within a mile or two of each of the mouths of the Mississippi is characterized by large swellings or upheavals of tough bluish-gray clay, to which has been applied the name "mud lumps." Many of these mud lumps rise just offshore and form islands having a surface extent of an acre or more and a height of 5 or 10 feet (see Pl. I, *A*), but some do not reach the water surface. They rise and subside at irregular rates, some of them suddenly, and they have been spoken of as the evil genii of the Passes, for constant vigilance is necessary to keep charts of these waters properly corrected. (See fig. 1.)

Almost all the mud lumps occur near bars at the mouths of the river. These bars are great piles of sediment which accumulate where the branches or passes of the river enter the sea. Their crests are naturally only about 10 feet under water, whereas for 200 miles upstream the river is 50 to 200 feet deep, but the United States engineers have made channels 30 to 35 feet deep and several hundred feet wide across the bars at South and Southwest passes. The natural bar of Southwest Pass and the changes made in it by the engineers are illustrated in Plate II.

An immense amount of traffic finds its natural course southward and eastward from the north side of the Gulf of Mexico, and this commerce, which is certain to augment, must be protected and the approaches to New Orleans improved and even their present large capacity increased. New Orleans, although over 100 miles from the sea, is now the fifteenth largest city and the second largest port in the United States, so that the seaward outlet for her commerce is of vital importance.

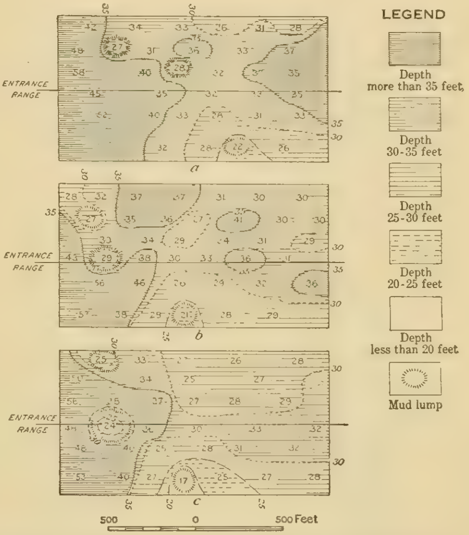

Figure 1.—Sketches showing depth and condition of channel at different dates and development of mud lumps at entrance of Southwest Pass. From data furnished by United States Corps of Engineers. The area lies in the middle of the channel and just outside the jetties. Sketches *a*, *b*, and *c* were prepared from soundings made Apr. 29, May 10, and May 19, respectively. One of the mud lumps rose in the middle of the channel where, on Apr. 29, there was 45 feet of water but on May 19 only 23 feet. Apparently some of the lumps shifted slightly in position and others subsided while new ones rose near by. The shape of the bottom here at any particular time is a result of the work of the river, the activities of the mud lumps, and the Government dredging operations.

The mud lumps are also of considerable purely scientific interest, for their development is not included in the usual concept of delta growth, and although several hypotheses concerning them have been advanced, their cause must still be regarded as uncertain.

PRESENT AND PRECEDING INVESTIGATIONS.

The present study of the mud lumps, which is a part of the Coastal Plain investigations of the United States Geological Survey, has been only begun, and this report is but a brief summary of existing knowledge of the mud lumps and of features and processes which may throw light on their origin. It includes some facts and ideas gathered in a few weeks spent at the mouth of the river in the fall of 1912 and the summer of 1913. On the first trip the United States engineers gave much assistance and furnished many important data, and on the second, through the courtesy of Dr. H. F. Moore, of the Bureau of Fisheries, the United States steamship *Fish Hawk* was made available for collecting samples of water and mud just offshore. T. Wayland Vaughan and others have furnished valuable suggestions and Prof. E. W. Hilgard and several members of the United States Engineer Corps and United States Geological Survey have very kindly read and criticized the manuscript.

Comparatively little geologic field work has been done on the problems of the Mississippi Delta or the mud lumps. Lyell and Hilgard have made the principal contributions, their results being set forth in several publications. Lyell's conclusions are summarized in his textbook, and Hilgard's in a recent paper entitled "A new development in the Mississippi delta," published in the Popular Science Monthly for March, 1912, and also in several papers published in the American Journal of Science in 1871. The engineering problems connected with the mud lumps have been extensively discussed, particularly in the annual reports of the United States engineers. The lumps are probably peculiar to the delta of the Mississippi, but, as Hilgard says, it seems remarkable that upheavals so extensive should escape discussion or even reference in most of the best textbooks on geology. Potonié,[1] however, has described a growth similar, in some respects at least, to the mud lumps and concludes that it was produced by marsh gas, clay having flowed into the cavity as the gas escaped, making the island permanent.

Several hypotheses concerning the cause of the lumps are worthy of consideration, though few have been set forth in print. Volcanism, faulting, the accumulation of bodies of rock salt or sulphur or oil like laccoliths below the surface, and the forcing up of the clay by hydraulic pressure transmitted through water from higher points to the landward through inclosed porous strata seem to be out of the question as causes of the phenomenon. The two ideas most favored have been (1) that the lumps are upheaved by gas, and (2) that the pressure of the constantly increasing deposits of the delta has in some way caused the upheavals.

Hilgard contends that the mud lumps owe their existence to the pressure of a layer of sand and silt, perhaps 30 or 40 feet thick, on a thinner layer of very fluid mud below, which in turn rests upon a stratum that he calls Port Hudson clay—a deposit very different from any being formed to-day. He believes that just offshore much river-borne colloidal sediment is being flocculated by the salt of the sea and is slowly settling, forming a layer of sludge; that a more granular and compact layer is built out on this sludge, giving rise to an unstable condition; and finally that wherever the crust, so to speak, is weakest the sludge is forced up to the surface through the weight of the sand and silt. It thus becomes of prime importance to determine whether or not the bottom offshore is very fluid mud.

When Capt. James B. Eads proposed to put in jetties at the end of South Pass to cause the river to scour deeper and do some of the work that the dredges had been doing in keeping a navigable depth of water over the bar Hilgard wrote to Eads saying that if this plan were put into operation a deeper channel would be scoured, but that the scouring would weaken the crust of silt so much that the fluid mud from below would break up through, obstructing the channel more seriously than the fine sand of the bar. Eads had encountered considerable objection to his plan of building jetties, but he was a man of both means and determination and his final proposal to advance the funds for building the jetties and ask no reimbursement until the desired depth of water was obtained was accepted. He replied to Hilgard that a surcease from the heavy burden of dredging for 20 or 30 years would be worth the cost of the

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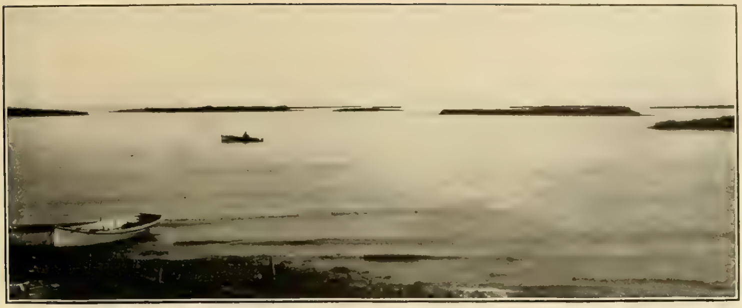
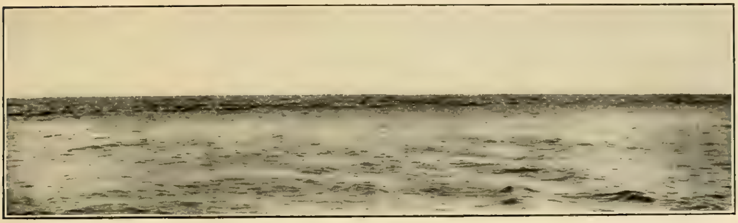
[1] Potonié, H., Eine im Ögelsee (Prov. Brandenburg) plötzlich neu entstandene Insel: K. preuss. geol. Landesanstalt zu Berlin Jahrb., Band 32, Teil 1, pp. 187–218, 1911.



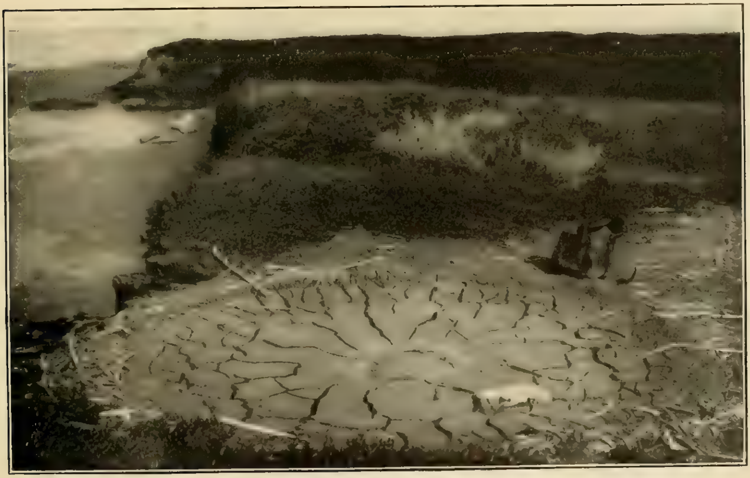
A. MUD-LUMP ISLANDS 2 TO 3 MILES SOUTHEAST OF PASS A LOUTRE LIGHTHOUSE.

All these islands have been formed in the last few years by the swelling up of portions of the sea floor, so recently that none of them are shown on the latest chart. Like other mud lumps they are comparatively flat-topped and concordant in height.



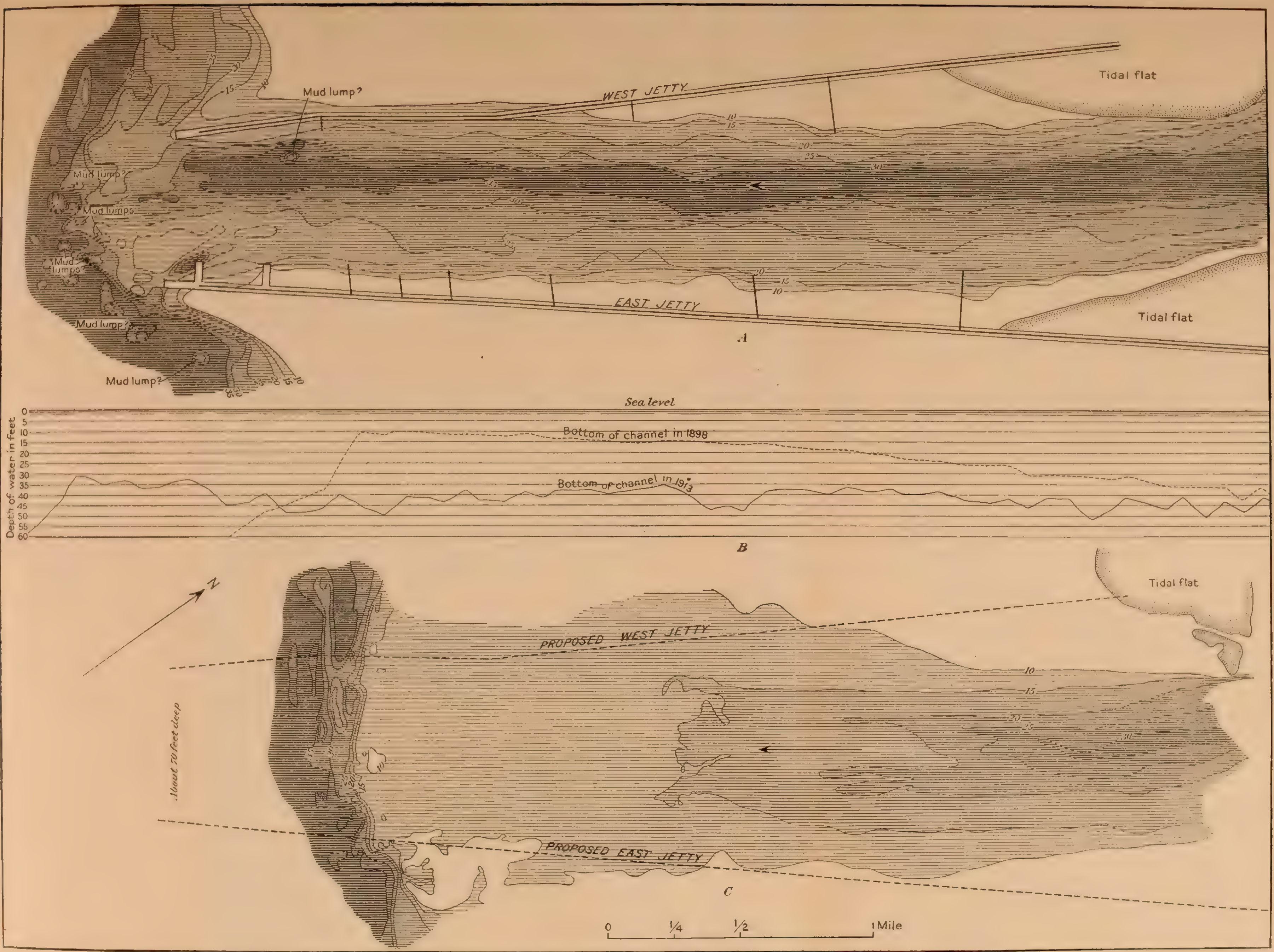
B. VIEW ABOUT 3 MILES SEAWARD FROM END OF SOUTHWEST PASS.

Showing light-colored, muddy river water in foreground and dark, clear sea water in distance. The boundary between the two is very sharp, and there seems to be also a difference in wave form between the clear and the muddy water.



C. MUD SPRING AT TOP OF WAVE-CUT CLIFF ON MUD LUMP 3 MILES SOUTHEAST OF PASS A LOUTRE LIGHTHOUSE.

This and the other photographs were taken in the low-water season, when the springs and mud lumps are least active. To judge by the fact that the rim of the "crater" has been built up only a few inches the discharge from this spring, even when most active, is probably very slight. These spluttering, volcano-like gas-mud springs seem a fitting accompaniment to the weird, silent, and unforeboded rise and subsidence of the islands.



MAP OF THE BAR AT THE OUTER END OF SOUTHWEST PASS.

Showing changes effected in the last 13 years by the building of jetties and dredging. From data furnished by United States engineers. *A* shows the pass as it is in 1913. *B* shows comparative profiles of the center of the channel in 1898 and in 1913. *C* shows the pass as it was in 1898, when the controlling depth on the bar was only about 10 feet. Corresponding positions are shown directly above and beneath each other. Whether any of the elevations on the crest of the bar in 1898 were mud lumps is not known, but the fact that at that place, which has since been deeply scoured, there are to-day no mud lumps and that on the crest of the present bar, where in 1898 there was over 70 feet of water, mud lumps are numerous seem to militate against the idea that "mud lumps commonly arise in a pass immediately inside of the steep upstream slope of the bar, * * * where the depth is greatest and where the bottom can therefore most readily yield."

jetties and begged Hilgard not to press his objection. Hilgard agreed but prophesied that mud lumps would appear within 30 or 40 years on the inner slope of the bar where the river was caused to scour most deeply. Forty years has passed and the appearance of a mud lump at the end of South Pass according to Hilgard's prophecy is the principal theme of his recent paper.

THE LOWER END OF THE DELTA.

AMOUNT OF AVAILABLE INFORMATION.

Geologists are exploring in greater or less detail about one-fourth of the earth's surface, the remaining three-fourths being covered with water. They have obtained much information concerning the underlying rocks and the geologic history of all lands but have learned so little of the sea bottom—both its underlying materials and its history in ages gone by—that the permanency of ocean basins is still a subject of discussion. The interpretation of ancient sedimentary deposits has reached an advanced stage, but not with the assistance of any large amount of exact detailed information on present depositional conditions and processes now in operation. Erosion has been studied in detail and the effects of its various factors have been carefully evaluated, but sedimentation appears not to have received its share of attention. The study of the composition, structure, and mode of growth of the Mississippi Delta is therefore of great interest, for here a new geologic formation is now developing and processes of sedimentation are operating rapidly and on a large scale.

The lower end of the Mississippi Delta seems to be a region much frequented but little known. Every year multitudes of people visit New Orleans, but travel is confined for the most part to the four or five main rail and water routes. Between these routes lie great areas of marsh which man has not put to his service and which are not often traversed either by naturalists or by others. Perhaps it has been thought that the mode of growth of the Delta is so simple and so well understood that investigation would reveal nothing new. The prevailing idea seems to be that deltas are built up regularly by the addition of topset, foreset, and bottomset beds, and that this process and the constant shifting of the network of channels constitute about all that happens. But numerous facts—for example, the fact that the mouths of the Mississippi are apparently not shifting—do not accord with this idea.

Notwithstanding the fact that the region is in some respects an uncomfortable dwelling place it has many attractive features. Mosquitoes are somewhat troublesome, particularly a few miles back from the open sea, and sand flies are abundant along the coast at certain times of the year. The marshes are commonly too soft for travel of any kind, so that houses and walks are built on piles a few feet above the marsh, the interior of which would be almost inaccessible were it not for the passes and bayous that ramify it. But the discomforts are more than overbalanced by the features of interest, especially in the autumn. Orange groves border the river from New Orleans down almost to the Head of the Passes, below which hunting, trapping, fishing, and oyster growing occupy the time of most of those not engaged in Government work or as pilots. The region abounds in water fowl and in rabbits, muskrats, and raccoons. The proximity of the sea almost precludes oppressive heat and the temperature rarely, if ever, reaches the freezing point. Laborers, however, sometimes cease working in winter on account of cold winds. Large areas in the newer part of the Delta are not forested; indeed, all the plants of the region seem to be marching toward the sea by groups in orderly fashion.

The most striking evidence that the Delta is little known is that its geography is quite different from that indicated on the latest charts. (See fig. 2.) No less than 100 square miles of land is represented on these charts as water, and, what is still more remarkable, many square miles of water are shown as land. All the best maps of the lower end of the Delta show a deep indentation, called Garden Island Bay, between South Pass and Southeast Pass. As a matter of fact, there is only a small reentrant between these passes, and the maps were out of date 15 or 20 years ago. The reason for the inaccuracy is that the territory between the passes is not often visited and has not recently been surveyed. The coast chart has been corrected from time to time, but only from data concerning the traveled passes.

GENERAL FEATURES.

In order to formulate working hypotheses concerning the mud lumps it seems necessary first to learn as much as possible of the composition, structure, and mode of growth of the Delta.

A considerable part of southern Louisiana is less than 10 feet above sea level and much of it is inundated every year, receiving at each inundation a greater or less amount of sediment. The land surface is also losing some material through solution and stream transportation, but on the whole it is being gradually built up, or at least it was being built up before the levees were built and much of the flood water was shut out. Along the border of this flood plain lie other lowlands, only a few feet higher but having an aspect so different as to soil, vegetation, and form of surface that they are easily distinguished. The highest land lies along the river, the banks of which slope gradually from heights 10 to 15 feet above low water at New Orleans to sea level at the mouths of the river, and the high-water profile has a similar decline.

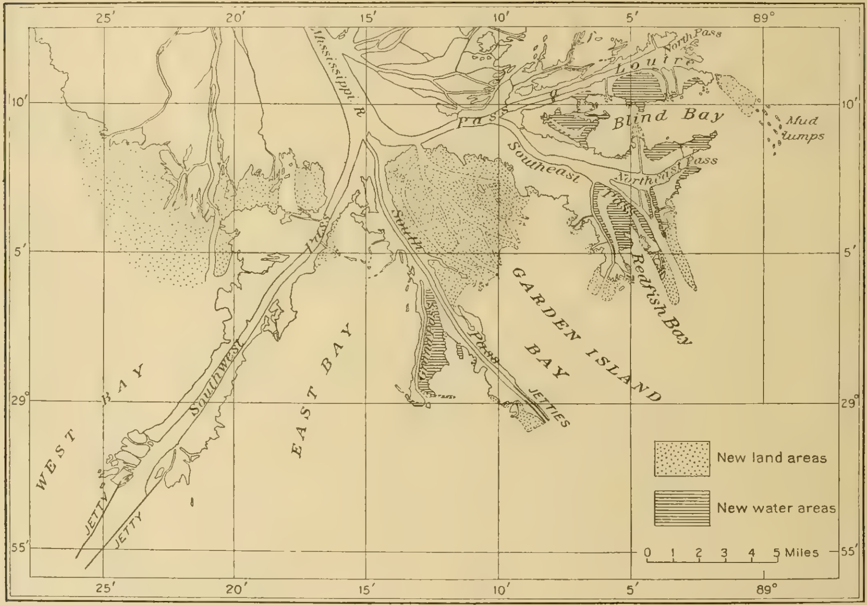


FIGURE 2. Sketch map of lower end of Delta of the Mississippi, showing approximately areas of land and water formed since the last detailed and complete survey was made. The coast chart has been corrected almost yearly for modifications in the territory immediately adjacent to the well-traveled passes, but not for the extensive changes that have taken place in the great marshes and bays between the passes. Although the Delta receives from the Mississippi about 400,000,000 tons of sediment every year and its front is commonly said to be advancing into the sea at the rate of 340 feet a year, the sea is at many places encroaching on the land. The immense amount of new land that has recently been formed in Garden Island Bay is a result of a crevasse that was formed several years ago near the Head of the Passes.

To an observer at the mouth of the river the idea that the region is a great dumping ground for a large part of the United States is most impressive. The land is being built out into the sea at an estimated average rate of about 300 feet a year, and although this estimate may be high, the rate is certainly rapid, as the constantly changing coast line and aspect of the vegetation bear witness. In some places it is much more rapid than others. In one place in Garden Island Bay the land appears to have advanced 2,000 feet in the spring of 1912.

Not only does the rate of advance differ from place to place, but the shore is in places actually retreating, not so much by sea erosion as by settling, which in places predominates over upbuilding.

COMPOSITION AND STRUCTURE.

It appears that in general the upper 50 feet, at least, of the deposits near the mouth of the river consist of thin layers of dark-blue clay and fine sand and a great many thin beds of intermediate character, each of which grades into the adjacent beds. Layers of clay almost free from sand and beds composed of a mixture of clay and fine sand are common, and the mixture of clay and sand is much more rigid than nearly pure clay.

Some of the material falls no doubt into the class known as topset beds, and some of it belongs to the foreset beds. Knowledge sufficient to afford a basis for classifying the beds by their physical character is not yet available. The topset beds at the head of the passes are probably at least 10 and not more than 100 feet thick, and along any pass they probably thin toward the coast. The deposits between the passes are more difficult to classify. The topset beds are on the whole most sandy and resistant near the passes and most clayey in the bays and marshes between; the foreset beds appear also to be in general coarsest near the passes, but the amount of sand they contain decreases not only laterally but downward for 40 or 50 feet, the lower material having no doubt been deposited in deep water some distance offshore. But there appear to be sandy layers throughout both topset and foreset beds, and all the strata are more or less lenticular.

The mechanical character of the sediment being deposited near the mouth of the river is shown in the following table:

Mechanical analyses of samples of earth obtained near the mouth of Mississippi River.

[Analyses made by Bureau of Soils, United States Department of Agriculture.]

No.	Locality.	Depth.	Fine gravel (2 to 1 mm.).	Coarse sand (1 to 0.5 mm.).	Medium sand (0.5 to 0.25 mm.).	Fine sand (0.25 to 0.1 mm.).	Very fine sand (0.1 to 0.05 mm.).	Silt (0.05 to 0.005 mm.).	Clay (0.005 mm. or less).
26196	½ mile east of Burrwood	5 feet below surface	0.0	0.1	0.2	5.5	64.0	27.0	2.9
26197	do	33 feet below surface	.0	.0	.1	1.4	1.4	48.9	48.0
26198	3 miles north of Burrwood	9½ to 10 feet below surface	.0	.0	.1	.8	20.6	68.1	10.4
26199	South side of Redfish Bay	6 feet below bed of sea	.0	.0	.2	.2	9.6	63.2	26.6
26200	Pilottown Wharf	10 to 10½ feet below surface	.0	.0	.1	.4	42.4	51.7	5.1
26201	2 miles west of Burrwood	2½ feet below water surface	.0	.2	.1	.6	22.0	58.6	18.6
26202	Point of land where South Pass and Southwest Pass separate.	12 feet below surface	.0	.0	.1	2.3	8.1	66.8	22.6
26203	Mud lump near Pass a Loutre.	9 feet below surface of mud lump.	.2	.3	.2	1.5	.6	39.2	58.0
26204	200 feet from river, Port Eads	11 feet below surface	.0	.1	.1	2.5	36.9	51.8	8.7
26205	Mouth of Mississippi River	Composite made up of 235 samples obtained below Head of Passes.	.3	.5	.2	6.5	28.2	51.2	13.0
	Average of all analyses except No. 26205		.005	.12	.14	2.17	23.38	52.65	21.39

The most important and impressive part of the above table is the analysis of sample No. 26205, which shows that fine gravel, coarse sand, and medium sand are present in the upper part of the Delta, though only in minute quantity. Fine sand makes up about one-fifteenth of the material and very fine sand a little over one-fourth. The great bulk of the material is silt, over one-half of all the particles measuring between 0.05 and 0.005 millimeter, or about 0.002–0.0002 inch. Even clay is present in the subordinate amount of 13 per cent, or a little more than one-eighth.

The chemical character of the material lying near the surface in the vicinity of the mouths of the river is shown in the following table giving a preliminary report of an analysis of the composite sample numbered 26205 in the above table, which is being made by George Steiger in the chemical laboratory of the United States Geological Survey, and also analyses of mud-lump clay and of river-borne sediment, made by Walter N. Howell.

Chemical analyses of air-dried samples of material from upper part of Mississippi Delta.

	1	2	3
SiO_2	69.9	62.36	63.71
Al_2O_3	10.6	17.34	16.17
Fe_2O_3			
FeO	3.4	2.31	1.93
FeS			
MgO	1.4	1.25	1.18
CaO	2.0	1.56	1.54
Na_2O	1.5	1.05	1.47
K_2O	2.3	Trace.	Trace.
H_2O below 100°	3.8		
H_2O at 100°		2.95	2.94
H_2O above 100°	2.6		
TiO_2	.6		
CO_2	1.4	8.91	8.13
Volatile and organic matter			
P_2O_5	.2		
MnO	.1	Trace.	Trace.
Cl.	.3	1.40	2.08
SO_3		.81	.74
Zr	.5		
	99.6	99.94	99.91

1. Composite made up of 235 samples collected by E. W. Shaw within 45 feet of surface in marshes and shallow water below Head of Passes, most of the material from the upper 20 feet of the Delta. George Steiger, analyst.
2. Sample of mud-lump clay from near Burrwood.
3. Sample of silt from bed of river near west side opposite Burrwood. Analyses 2 and 3 made for United States engineers by W. N. Howell.

In order to determine the character and arrangement of the material in the Delta, a sampling rod was used for getting samples beneath the surface, the rod being pushed down to the place where it was desired to take the sample. The various degrees of resistance of the sands and clays, or rather sandy silt and clayey silt, were thus readily noted. The "quicksand" of the Delta is not so quick or fluid as the clay. The sampler passes very easily through beds of clayey silt but can be forced only with difficulty through layers containing a considerable amount of sand, and often the sand prevents it from reaching a depth of 20 feet. The sand is so much more resistant than the clay that piles sunk in New Orleans for the larger buildings are driven down through clay and silt to a comparatively thick bed of sand that lies 60 to 80 feet below the surface and serves as a firm foundation.

It appears that the most rigid material in the Delta is a mixture of sand and clay in certain definite proportions. Crusty layers "as hard as asphalt" are sometimes reported, and it seems probable that such layers do not consist of iron oxide or other uncommon material but of a sand-clay mixture, and that there is every stage of gradation between this unusually resistant material and the very fluid clays. Experiments are now being made with mixtures of sand and clay which it is hoped will furnish further information on this subject.

The total thickness of the material properly referable to the Mississippi Delta is not definitely known but is probably at least 2,000 feet. The shape of the rock basin on which this material rests is also unknown; its sides may be concave or convex, and some think that it is traversed by a large central trench. Several wells have been sunk 2,000 feet or more into this Delta material, and although logs of some of them have been kept and fossils preserved, the identification of the beds is still uncertain. An unusually large amount of data seems to be needed to determine positively the age of these strata.

The general character of the Delta material down to a depth of about 1,000 feet is illustrated by the record of a well drilled in 1895 on the Magnolia sugar plantation, on the west bank of Mississippi River, about 45 miles below New Orleans. The well is owned by ex-Gov. H. C. Warmouth, who furnishes the following record:

Record of well on Magnolia sugar plantation.

	Thickness.	Depth.
	Feet.	*Feet.*
Soil, black, alluvial	40	40
Sand, fine	30	70
Clay, stiff	50	120
Sand and soft mud	40	160
Clay, hard, blue	200	360
Sand, pebbles, and small shells	210	570
Clay, very hard, blue	377	947
Sand, with salt water shooting above the well with gas	33	980

Silt is accumulating just offshore at the rate of several inches a year, as may be shown by taking a profile of the ocean bottom adjacent to the mouths of the river and drawing a parallel line to correspond to the estimated annual seaward advance, about 300 feet. (See figs. 3 and 4.) The character of the material deposited appears to vary from season to season. During the period of high water, which generally includes the first half of the calendar year, the sediment is noticeably coarser than during the period of low water, which includes roughly the second half of the year. The apparent result is a structure somewhat resembling the annual rings of growth of trees. As the sampling rod is forced into the earth it moves downward easily for a few inches, and then with difficulty for a few inches, and so on, in alternation. The minuteness and legibility of the record remain to be determined, but the principal floods and the principal times of drought are probably recorded.

The material collected by the *Fish Hawk* expedition from the bottom of the Gulf off the mouth of the Mississippi also indicates that the deposits consist in general of alternating layers of sandy and clayey silt. The dredges brought up from the bottom a mixture of dark clay and light gray sandy slime, the two apparently coming from different layers. The core samples consist uniformly of stratified material with stiff clay or sandy clay at the bottom and beds of increasing fluidity to the top, which is nearly clear water. The most compact material was found near the ends of the Passes in less than 5 fathoms of water.

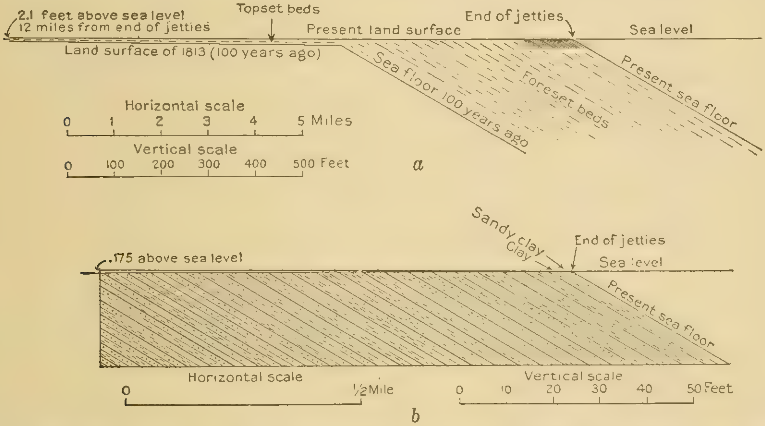


FIGURE 3.—Profiles showing present and past land surface and sea bottom near mouths of Mississippi. *a*, Generalized profile of present land surface and sea bottom from the Head of the Passes to a point 4 miles beyond end of South Pass jetties and also of position of corresponding surface 100 years ago. Shows the great thickness of the foreset beds of the Delta as compared with that of the topset beds, which apparently would be only about one-tenth as thick as they are if they were not affected by subsidence. In order to show the topset beds at all it is necessary to exaggerate grossly the vertical scale. *b*, Enlarged section of the foreset beds represented by the finely ruled portion of *a*, showing annual and seasonal growth layers. The estimated advance of the bars at the mouths of the Passes of 340 feet a year is believed to be considerably greater than the average rate at which the land is pushing out to sea. The above diagrams represent an annual advance of 265 feet, which is possibly too large.

PROCESSES AND CONDITIONS AFFECTING MODE OF GROWTH.

Certain features of the Delta suggest that it is affected by a process which heretofore seems not to have been suspected, namely, a bodily flowage toward the sea. The surface receives a new layer of sediment at each flood, but its altitude above sea does not seem to show a corresponding increase. Timbers and other objects left on the surface appear to sink down into the earth, and on careful examination it becomes evident that the Delta is sinking as well as building upward and outward, the coast being most affected. The tide-gage records at Port Eads show a gradual increase in the apparent height of mean tide from 2 feet 20 years ago to 4 feet now;

in other words, that part of the Delta is sinking at a rate of a tenth of a foot a year. The shape of the sea bottom just offshore suggests local bulging of the Delta front, for it is characterized by irregular swells and hollows which change from time to time in form and position and by an absence of well-defined channels. In 1905 and 1907 shoaling was reported fully 25 miles southeast of Port Eads, depths of only 65 to 100 fathoms being found where before the depth was 300 to 600 fathoms. The character of the coast itself in places where sedimentation is not now rapid strongly suggests subsidence, especially the coast near Barataria Bay and on Breton and Chandeleur sounds. In these areas the boundary between land and sea is intricately irregular, small islands rise just above the sea, and shallow lakes and bays are abundant. The shore features seem to be just those which would result from gentle subsidence of a low-lying, slightly uneven surface. The sinking is due in part, no doubt, or perhaps entirely, to the compacting of the sediment. Whatever its exact nature, the facts that the subsidence is greatest where the Delta is growing most rapidly and that because of the very watery condition of the material it is presumably becoming more compact make it seem probable that the process is only in part, if at all, one of isostatic adjustment. At a depth of 5,000 feet there may be no downward movement.

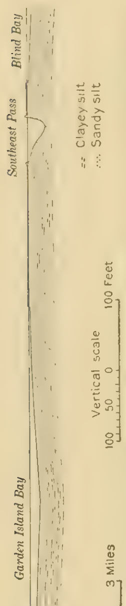


FIGURE 4.—Cross section from south-southwest to north-northeast through Port Eads and Balize, showing profile of sea bottom and marsh surface and character and distribution of recently deposited sediment, but not their relative thickness and attitude. Sandy silt is most abundant near the Passes and at the top of the comparatively steep slope (about 60 feet to the mile) offshore; clayey silt predominates in shallow bays and marshes and at the bottom some distance offshore. Both the clayey silt and sandy silt are thinly stratified. Not only are the laminæ too thin to be shown individually but also the groups of laminæ, having a thickness of several inches, which appear to be annual growth layers.

However, certain facts suggest that in comparatively late geologic time this region has been affected by crustal deformation. Deposits which outcrop in a district farther north and which have been described as the Lafayette formation, the loess, and the Port Hudson clay have been thought to indicate general elevation and subsidence, and in the vicinity of New Orleans, at least, coarse sand evidently deposited in shallow water occurs at various depths down to 3,000 feet, but in addition differential uplift appears to have occurred in the vicinity of Natchez. Otherwise the gravel, which contains pebbles brought apparently from Canada and lies as much as 200 feet above the present stream, calls for an extremely low gradient upstream and an almost impossibly high gradient downstream. The narrowness of the flood plain at Natchez and the outline of the area less than 100 feet above sea level, this area being considerably broader above than opposite Natchez, suggest the same conclusion.

In this connection it is interesting to note that in the recent determinations of intensity of gravity made by the Coast and Geodetic Survey the earth near New Orleans was found not to have an excess of mass, as might be expected from the vast amount of sediment which has accumulated there, but a deficiency equivalent to a lack of about 430 feet of strata. In other words, if the surface at New Orleans were buried under 430 feet of solid rock, the district would then be in approximate balance with the rest of the world.

Below Baton Rouge the river flows southeastward and the great body of the delta has developed in that direction. It is only about a third as far from Baton Rouge to the sea in a southwesterly direction as it is in a straight line to the mouths of the river. The reason for this trend may be that a westward littoral current tends to throw the sediment in that direction from the mouths of the river and in this way to crowd the outlet eastward, but the known facts do not appear sufficient to warrant a definite conclusion.

The protruding character of the coast at the mouth of the river is a somewhat striking testimony against the idea that subsidence always produces deep bays. The form of a coast depends on many factors—sedimentation, erosion, deformation, and the nature and extent of the work done in previous cycles.

Hilgard has pointed out that the Mississippi Delta differs markedly from other deltas, and also from an ideal delta. He says:[a]

> The bird-foot shape of the lower Mississippi Delta, with deep embayments in between, is unexampled in any other large river delta in the world. The bays between the delta fingers ("passes") are being very slowly shallowed, chiefly by wave and tidal action from the Gulf carrying in the bar sands, and only subordinately by river overflow. The river in this lower delta region is for 50 miles below Fort Jackson bordered by narrow banks of unyielding gray clay, between which is carried the entire volume of the river through the narrow-banked "neck" until it reaches a common point of divergence, the Head of the Passes, whence similarly narrow-banked channels diverge, unbranched, in bird-foot form.
>
> The usual shape of a normal delta is a convex protrusion beyond the main shore line, with usually slight protrusions at the mouths of the distributaries, as can be seen by an inspection of the maps of the deltas of any of the larger rivers, such as the Nile, Ganges, Brahmaputra, Danube, Volga, Lena, and others. Within the delta areas of these streams large and small distributaries form a complex network, frequently changing at times of high water. No such changes are shown by the narrow-banked, diverging arms of the lower Mississippi Delta, which steadily advance into the Gulf singly, and without any permanent distributaries being formed. The only approach to the form and structure of an ordinary delta occurs about 3 miles above the Head of the Passes, on the east side, where small and shallow channels connect with the main river through Cubit Gap, a shallow lateral outlet.

The typical delta developments at Cubit Gap, at the Jump, and in Garden Island Bay, not yet represented on charts, have resulted from unusual conditions—accidents, so to speak—in the course of delta development. The full history of the land development at the Jump is not known, but in the other two places, and probably at all three, the river has broken through narrow banks which separated it from the sea, and very rapid sedimentation has followed. The astounding fact in this connection is that the river does not more frequently cut through its narrow banks, although it often overflowed these banks before the levees were built, during a time when the present features were developing. At Bird Island Sound the river might reach sea level in a quarter of a mile, but instead it takes a course of about 25 miles. Just below New Orleans the river might reach sea level by flowing eastward less than 10 miles through territory subject to overflow, but instead it flows fully 100 miles southwestward. Hilgard believes that these remarkable features are due to "a compact, impervious gray clay, corresponding exactly to the material constituting the mud lumps," clay which "so long as it remains submerged or fully wetted * * * resists erosion to a remarkable degree." To the present writer, however, this inference does not seem well founded. The exposures and borings along the river banks show a large proportion of fine sand, which is easily washed. Several borings were made at and near the Head of the Passes to test this point and sand was found in all of them. (See the mechanical analysis of sample No. 26202.) Clay is present in places and may possibly be the remains of old mud lumps, but a large part of the material appears to be incoherent sand. To-day the coarsest sediment is being deposited on or near the river banks, where it accumulates to such an extent as to form natural levees that border the river almost if not quite to the sea, and just offshore in the immediate vicinity of the ends of the passes. The finer particles are carried by the river water in times of overflow into the marshes at some distance from the river and by the sea water at all times into the bays between the passes and to a large surrounding area of deep water lying at a distance greater than 2 or 3 miles from the river mouths. As indicated in figure 4, the sandiest material found in the borings lay near the river banks and the most clayey material in the marshes several miles from the river.

All the movements of the sea water at the mouths tend to sort out the finest sediment there discharged and carry it to distances depending in part on the size of the particles. In a few places, particularly in the most exposed positions, as at the outermost ends of the passes and also where the sediment is accumulating slowly, as in Bird Island Sound, this process goes so far as to develop sand beaches. The very fine material consists not only of the finest solid particles, brought down in that form by the river, but also of matter transported in a colloidal form and flocculated by the salt of the sea, and it is commonly apparent in the water 10 miles or more from land. At times and in places the line between the muddy and the clear water is very sharp, as shown in Plate I, *B*.

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[a] Hilgard, E. W., A new development in the Mississippi Delta: Pop. Sci. Monthly, March, 1912.

Thus it seems to the writer, both from field evidence and from indirect theoretical considerations, that the river banks consist not of clay which, though yielding to pressure, is so resistant to corrasion that it determines the location of the river channels, but of sand which is resistant to pressure and yielding to water currents, with perhaps some mud-lump clay here and there. It seems probable that the form of the river here, as elsewhere throughout its course below Cairo, must be produced in detail by a balance among the hydraulic forces involved in the river flow; that the stream is so large and powerful that no clay could long prevent it from cutting just such a channel as a balance among its forces demands. Yet this must be regarded only as a suggestion, for although much is known concerning the hydraulics of river flow many phenomena are not yet fully understood. For example, above Baton Rouge the river is broad and very shallow, carries much coarse sand, and has a tendency to meander which seems beyond human power to control, whereas below that city it is little more than half as broad, is 100 to 200 feet deep, has little tendency to meander, and seems adjusted to its load of very fine sand and silt and quite competent to carry it. To the writer it seems probable that the peculiar form of the river near its mouths is related in cause to these phenomena.

The offshore movement of the river water is indicated by the following analyses of samples, most of which were collected on the *Fish Hawk* expedition. The samples that show the largest amount of chlorine are, of course, those that contain the least river water. The regularly greater chlorine content of the bottom samples accords with the conditions elsewhere and is due to the fact that river water, having less density than sea water, flows out at the surface of the sea. The table includes also analyses of a few samples of sludge from springs on mud lumps.

The examinations of chlorine in this table were made by E. C. Bain, under the direction of R. B. Dole. The tests were made by means of a salinity outfit supplied by the Copenhagen laboratory of the Conseil Permanent International de la Mer, which was obtained through the courtesy of the United States Bureau of Fisheries. The procedure is an adaptation of the usual method of estimating chlorine by titrating with silver nitrate in presence of potassium chromate. An essential feature is a sealed tube of standard sea water whose content of chlorine has been very carefully determined. This water is used for comparison, and the pieces of the apparatus are so constructed and calibrated as to insure maximum accuracy. Standard sea water No. P_7 2/2, 1912, with a chlorine content of 19.386 grams per kilogram, was used, but as only a little of it was available, a large sample of nearly normal sea water was very carefully titrated and used for frequent comparison during the tests. Float burette No. 8, measuring about 1.5 millimeters between gradations, and pipette No. 3, having a capacity of 15.04 cubic centimeters, were used.

Table showing chlorine content, specific gravity, temperature, and other data concerning water samples collected near mouths of Mississippi River.

[The measurements of specific gravity are only approximate and subject to a correction of ± 0.002, the average error being probably not over 0.0005; distances are given in statute miles and bearings are true; samples were collected on June 22, 23, 24, and 25, 1913.]

Station No.	Location.	Depth of water (feet).	Position of water.	Chlorine (grams per kilogram).	Temperature (° F.).	Specific gravity.
7900	84 miles from Galveston and 29 miles S. 51° E. of Sabine Bank light	57	Surface	13.60	80	
			Bottom	18.73		
7901	11 miles S. 74° E. of Trinity Shoal buoy, about midway between Galveston and Southwest Pass.	48	Surface	15.76	80	
			Bottom	17.22	79	
7902	35 miles S. 71° E. of Trinity Shoal buoy	63	Surface	16.90	80	1.019
			Bottom	17.64	79½	1.0205
7903	20 miles S. 42° E. of Timbalier Island light, nearly 50 miles west of Southwest Pass.	102	Surface	13.42	82	1.015
			Bottom	19.91	74	1.02425
7903.1	About 8 miles west of ends of Southwest Pass jetties		Surface	13.65		
7903.2	About 3½ miles west of ends of Southwest Pass jetties. (Clear water.)		Surface	15.62		
7903.4	About 3 miles west of ends of Southwest Pass jetties. (Yellowish muddy water.)		Surface	5.08		
7904	1½ miles S. 11° W. of light on east jetty of Southwest Pass	72	Surface[a]	8.63	80½	1.0095
			Bottom		77	
7905	3 miles S. 45° E. of lightship just outside of Southwest Pass	228	Surface	2.11	81	.998
			Bottom	17.79	72½	1.021
7906	7½ miles S. 33° E. of lightship just outside of Southwest Pass	357	Surface[a]	12.64	82½	1.013
			Bottom	19.28	77	1.0235
7907	7⅝ miles S. 17° E. of station 7906	585	Surface	14.46	82	1.015
			Bottom	19.05	79½	1.022
7908	1½ mile S. 17° E. of east jetty light, South Pass	102	Surface	5.86	82½	1.00525
			Bottom		73½	
7908a	About 600 feet below surface of sea and about 18 miles S. 16° W. of South Pass light.			19.99		
7908b	1½ miles S. 80° E. of east jetty light, South Pass		Surface	.36		
7909	14½ miles S. 45° E. of Southwest Pass light; 14½ miles S. 16° W. of South Pass light.	456	Surface	13.88	81	1.015
			Bottom	19.85	71	1.0235
7910	8¼ miles south of South Pass light	306	Surface	7.42	79	1.00825
			Bottom	17.12	69	1.021
7910	Same, plunger sample	306	Bottom	19.81		
7911	6½ miles S. 45° E. of South Pass light	252	Surface	9.15	80	1.010
			Bottom	19.69	64½	1.0235
7911	Same, plunger sample	252	Bottom	19.53		
7912	9¾ miles S. 50° E. of South Pass light	336	Surface	13.62	81	1.0135
			Bottom	19.97	66½	1.023
7913	12½ miles S. 51° E. of South Pass light	732	Surface	14.16	81	1.014
			Bottom	19.82	67½	1.024
7914	10 miles S. 82° E. of South Pass light	288	Surface	10.60	82	1.0115
			Bottom	18.47	76½	1.0225
7915	10½ miles N. 78° E. of South Pass light	204	Surface	6.71	83	1.006
			Bottom	19.27	68½	1.023
7916	6¼ miles S. 28½° E. of Pass a Loutre light	72	Surface	2.66	84½	1.000
			Bottom	6.24	72	1.00625
7917	5 miles S. 36° E. of Pass a Loutre light	16	Surface	1.65	85	.9985
			Bottom	10.70	78	1.0125
7918	7½ miles S 47° E. of Pass a Loutre light	126	Surface	2.67	86	1.000
			Bottom	2.62	68	1.000
7919	11½ miles S. 51° E. of Pass a Loutre light	330	Surface	9.01	83	1.00925
			Bottom	19.79	64	1.02425
7919	Same, plunger sample	330	Bottom	19.83		
7920	5½ miles S. 56° E. of station 7919.	486	Surface	12.79	82½	1.013
			Bottom	18.14	74	1.021
7921	46 miles N. 39° E. of station 7917	102	Surface	13.52	82½	1.014
			Bottom	17.08	73	1.022

[a] Strong odor of hydrogen sulphide. Gas driven off by boiling before determination of chlorine.

Chlorine content of additional samples, in grams per kilogram of water.

Surface sea water in West Bay ¼ mile north of first lump north of Bald Lump, 1 mile west of Burrwood, La.; Nov. 15, 1912, depth 8 feet	7.68
Black mud spring on minor Cactus lump, Burrwood, La., 1 foot below surface of water; Nov. 16, 1912	15.99
Mud spring in marsh 1 mile east of Spanish Fort; Nov. 17, 1912	18.81
Sludge from mud spring on fourth right mud lump off Pass a Loutre (Mud Spring special No. 3); Nov. 20, 1912	17.18

The following data may be used for comparison:

Chlorine, in grams per kilogram, contained in water taken from different places.

Average for Mississippi River at New Orleans for 1905–6. (Analyses by J. L. Porter, chemist, New Orleans Water and Sewerage Board, U. S. Geol. Survey Water-Supply Paper 236, p. 77, 1905)	0.0097
Sea water from southwest channel, Tortugas, Fla. (Sample collected in May, 1912, and tested at the Plymouth, England, laboratory)	19.99
Average of 52 samples collected in May and June, 1913, from southwest channel, Tortugas, Fla. (Determinations made by R. B. Dole, U. S. Geological Survey)	19.95
Average content of normal sea water. (Standard sea water, P_7 2/2, 1912, issued by the Conseil Permanent International de la Mer)	19.386

The principal processes affecting the lower end of the Delta may be summarized briefly. The most important is the building out of the coast line through the accumulation of sediment brought down by the river, the rate of progradation varying from season to season. Throughout the lower part of the river's course it tends to build natural levees—that is, to make the land near the river higher than that at a distance—and this tendency or a stiff clay or some other factor has caused the delta to assume a bird-foot form. Littoral currents and practically all other movements of the sea water tend to spread and sort the sediment. These movements vary greatly from time to time and the method and extent of the distribution of sediment are unknown, though probably more sediment goes westward than eastward. The beating of the waves, though much less severe than in many other regions, produces some modifications of the shore line. General subsidence, perhaps brought about by simple compacting and perhaps by bodily flowage, allows the sea to encroach on the land where sedimentation is not most active. Plants advance seaward by groups and check the transportation of sediment in the areas of which they take possession. Lastly, there is this strange growth of mud lumps, which plays an important part in arranging the material within the delta and perhaps also, as Hilgard thinks, in locating and permanently confining the river channels.

THE MUD LUMPS.

The mud lumps generally lie within a mile of the end of a pass, no pass being entirely free from them, and are most numerous on the right side of each channel. One is now active 1 mile south of the old Spanish magazine, 2 miles north of the mouth of Balize Bayou, and perhaps its development is due to the fact that this bayou has recently become much enlarged. A few others have been reported at somewhat greater distances from the end of a pass, but most of them cluster rather closely about the outlets of the river. Just now they are most numerous south of the end of Pass a Loutre, a chain of 20 or 30 lumps having developed in this district in the last few years. North, Northeast, and Southeast passes each contain a few. South Pass contains four or five, and Southwest Pass about a dozen.

The lumps are commonly 20 or 30 rods broad and stand 20 or 30 feet above the adjacent bottom. With reference to sea level their heights are somewhat closely concordant, few extending more than 8 or less than 2 feet above the water. They are rounded or elliptical at first but their exposed portions are soon carved into irregular shapes and some are cut in two by wave action. Their growth occupies from a few hours to several years and is usually irregular. Generally a mud lump rises in a few weeks or months to a height of 4 or 5 feet above the surface of the water. Then it remains quiescent and is beaten down by the waves in the course of a few years. Many of them subside, however, and some have disappeared in a night. Those that rise slowly are considerably worn before they stop growing. Those that rise more rapidly and in protected places are capped by laminated silt having a maximum thickness of 10 feet. The lumps are appreciably more active during and immediately after high water. This is well shown in figure 5. Concerning the date given in this figure Mr. J. L. Hortenstine, of the United States Corps of Engineers, says in a letter:

> There was deposited in this area a total of 2,500,000 cubic yards of material during the recent high stage of the river. This material was deposited during the months of March, April, and May, 1913. The additional material caused an increased pressure over the area of 1,800,000 tons, or a mean pressure of 400 pounds per square foot. The maximum pressure is found at a distance of 600 feet upstream from the chain of mud lumps shown on chart No. 5 [fig. 5, *a*] and this pressure is approximately 825 pounds per square foot.

The stories related by sailors and pilots concerning the mode of growth of the mud lumps are fairly consistent. One man states that the growth of a mud lump was accompanied by a rather loud roar as it rose above the water, and another states that he once saw flashes of light rising from a mud lump, but these statements are very different from the great mass of testimony concerning the lumps, and it seems probable that they are not based on fact.

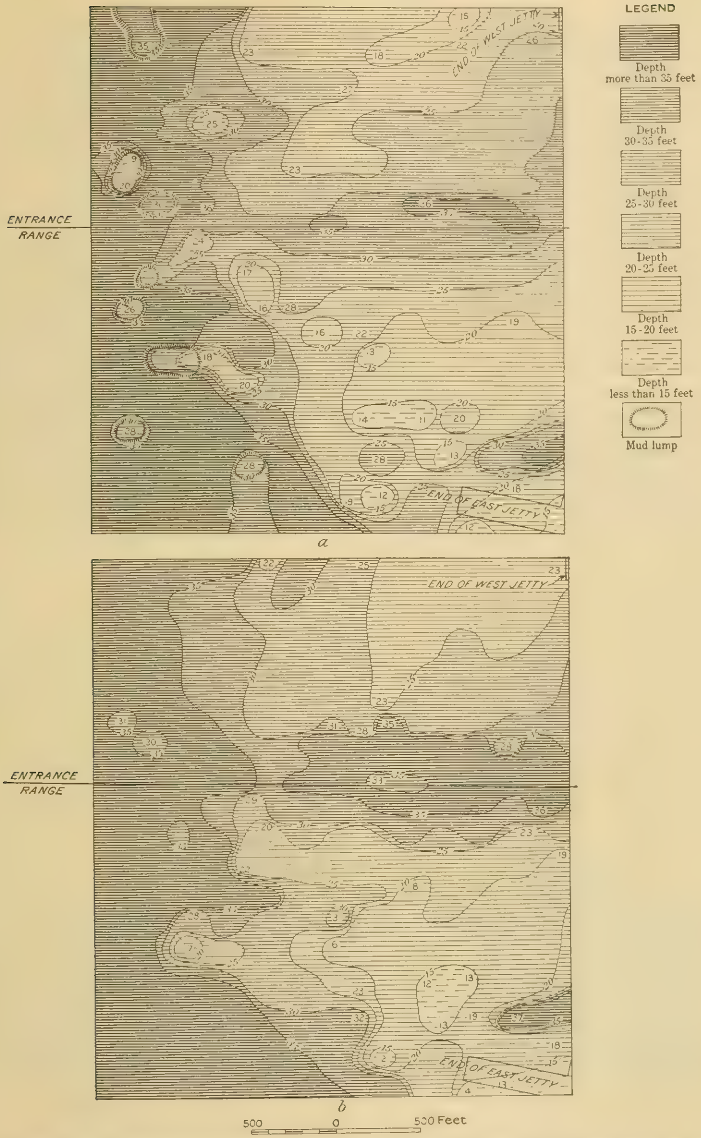


FIGURE 5.—Two charts of the entrance to Southwest Pass. *a*, Chart showing activity of mud lumps from May 20 to June 6, 1913, at the close of a high-water period; *b*, Chart showing mud-lump quiescence from August 1 to 13, 1913, during a low-water period, when the apparent absence of lumps is due to subsidence (perhaps through movement elsewhere and perhaps through the removal of the surplus load of water) or to cutting away by degrees and to filling in the hollows between with sediment. From data furnished by United States Corps of Engineers.

The structure of the mud lumps appears to be comparable to that of bysmaliths. (See fig. 6.) A dark bluish-gray clay of medium stiffness and great stickiness forms the central core. As shown in the analysis of sample No. 26203, this clay contains some sand and silt, though not in amounts sufficiently large to affect its consistency perceptibly. Upon and around the clay core lies a series of faulted and folded strata of sand and silt which have been carried up from the sea bottom and deformed in the upheaval. The upper parts of the mud lumps bear numerous fissures and some normal faults, fine examples of block faults being common. A peculiarity of many of the new mud lumps is that their surface resembles a plowed field, being covered with irregular furrows running in every direction. This effect, which has excited much wonder, appears to be the result of slight erosion on an extensively fissured surface.

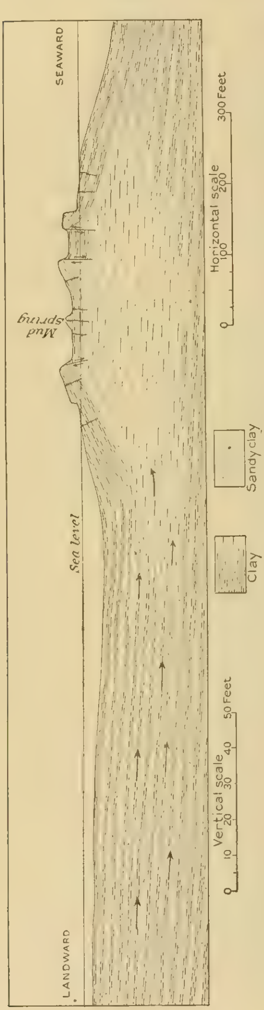
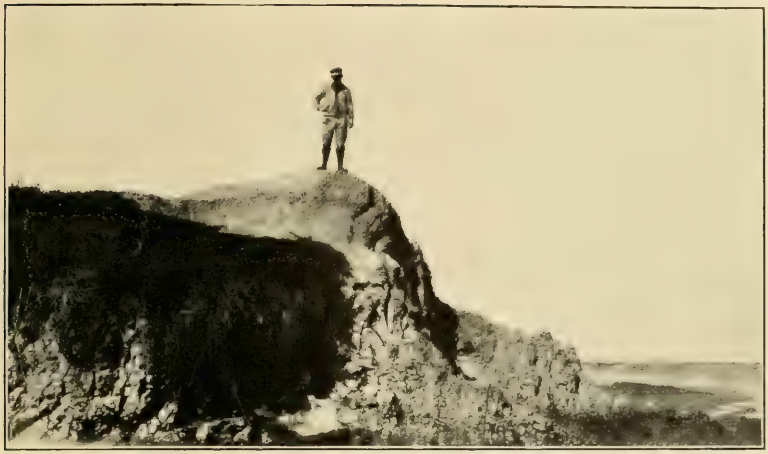


FIGURE 6.—Partly hypothetical cross section of eighth mud lump southeast of Pass a Loutre Lighthouse, showing the great clay mass in the interior of the lump, the deformed clay and sandy clay strata above and at the sides, and the similar undeformed material below. The arrows show the supposed flowage of the clay layers from the landward side, and the corresponding thinning of the clay layers on that side. The central part of this lump has apparently settled, but the central parts of other lumps have been faulted upward.

One of the most significant facts concerning the mud lumps is that they contain much more clay than has been found in other parts of the Delta deposits. Borings, several of them 45 feet and many of them 35 feet deep, were sunk in the mud lumps in the fall of 1912, and they show that most of this material is structureless clay. Similar borings in other places in the region have found stratified materials containing much sand. Sandy layers also commonly occur above and below the massive clay of the mud lumps. A radial series of borings made on a mud lump about 2 miles west of Burrwood showed that the clay decreases and the sandy material increases in thickness away from the center of the lump. This strongly suggests that the mud lumps have been produced by the lateral flowage of soft layers of clay, for no such thick strata of clay have been found elsewhere in the Delta.

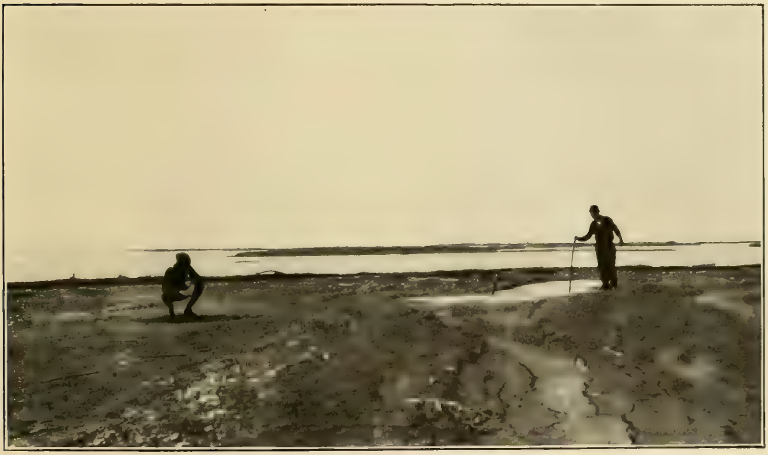
The color of the clay, though generally dark bluish or greenish gray, appears to change under certain conditions to chocolate or reddish. Such tints are common along cracks and are developed in some of the cones built up by the springs on the lumps. On drying, the gray clay becomes somewhat lighter in color and crumbles, as shown in Plate III, *A*. In this behavior and in its general appearance it resembles the "buckshot" clay of northern Louisiana and adjacent territory and the very sticky and somewhat mucky clay that is commonly deposited in marshes. The clay is so stiff that even where wet one may walk upon it without sinking more than a few inches; in fact the surface of the mud lumps is the firmest to be found below Head of the Passes. Hence, although the mud-lump islands are easy to reach and cross the lumps surrounded by marsh are very difficult of access.

In the hope that organisms or organic remains might be found in the clay which would show whether it is of marine or fresh-water origin, seven samples were examined by Dr. Albert Mann, of the United States Bureau of Plant Industry, a special search being made for diatoms. Concerning them he says:



A. WAVE-CUT CLIFF ON GIBRALTAR MUD LUMP, RED FISH BAY.

The mound on which the man stands was built by a mud spring now extinct, and its crest is nearly 15 feet above mean tide, a height considerably greater than most mud lumps attain. On the left is shown a luxuriant growth of grass such as commonly flourishes on mud lumps.



B. MUD LUMP $3\frac{1}{2}$ MILES SOUTHEAST OF PASS A LOUTRE LIGHTHOUSE.

The men stand beside mud springs each of which is associated with a fissure. In the distance are other mud-lump islands.

None of these samples are in any true sense mud containing diatoms. * * * I am not at all certain that all the diatoms here listed would not be found in any sample of mud located in or near the mouth of a river. * * * The rare specimens of diatoms discovered by great labor are not sufficiently frequent to indicate a marine or fresh-water origin for any of the material.

MUD SPRINGS.

Among the most conspicuous and impressive features of the mud lumps are the mud springs that are active on many if not all of them. (See Pl. I, *C*.) The discharge from these springs consists of salt, watery mud (sludge), and gas. The amount of sludge discharged is very small and the flow of gas is only 5 to 10 cubic feet an hour. When placed in a bottle the sludge settles readily, leaving clear water at the top. Owing probably to evaporation and to a variable admixture of rain water the saltness of this water ranges from somewhat more to somewhat less than that of sea water. The mud slowly accumulates around the vents and forms cones ranging in height from a few inches to several feet (see Pl. III, *A*), resembling miniature volcanoes.

Careful examination reveals the fact that many and perhaps all of the gas-mud springs are closely associated with fissures. (See Pl. III, *B*.) Commonly the fissures are so nearly obliterated that it is difficult to make sure of this fact, but on the freshest lumps both the association of the springs with fissures and their absence between fissures are evident. It seems, therefore, that when a lump is pushed up its upper part, especially the sand and silt cap, is somewhat extensively fissured. Water rises in the fissures at least to the level of the sea, and gas bubbles rise through the water, causing erosion of the sides of the fissure. In places along fissures where conditions are favorable the rise of gas bubbles causes sufficient erosion to keep a vent open long after the remainder of the fissure closes entirely. The delta materials contain a large amount of both marsh gas and water, so that wherever a hole a few feet deep is made it almost immediately fills with water and bubbles with gas.

The following considerations seem to militate against the idea that the sludge discharged by the springs comes from a buried thick layer of flocculated clay. (1) The sludge settles readily, leaving clear water at the top. (2) The flow is small, irregular, and long continued. (3) The sludge in each spring has the color of the surrounding material. Two miles west of Burrwood there are two springs less than 100 feet apart, in one of which the sludge is yellowish and in the other nearly black. In the former the sludge rises through laminated yellowish silt and in the latter through dark-gray clay. (4) The bottoms of several mud lumps of various ages seem to have been reached and no layer or reservoir of sludge has been found.

It may be added that similar springs are associated with fissures elsewhere—for example along Steeles Bayou, just north of Vicksburg. Here the springs rise in fissures in an oversteepened bank. Where the quantity of water is considerable a clear stream flows from a small depression like an ordinary spring, but where it is small and the water emits bubbles of marsh gas the sides of the vent are eroded, the water becomes very muddy, and the slight overflow, accompanied by evaporation and absorption of water, leads to the growth of cones.

This hypothesis of the origin of the mud springs seems to be further supported by the fact that the vents are commonly constricted at the top, where they are only at certain times covered with the bubbling fluid mud and hence subjected to less wear than the deeper parts. Most of the vents are only a few inches in diameter at the top but widen to 1 or 2 feet a short distance down. The sounding rod, which was pushed down to a depth of 40 or 45 feet in many of the vents, penetrated 2 to 9 feet of thin watery mud, then thicker and thicker mud to a depth of 10 or 15 feet, where it encountered ordinary, somewhat stiff mud-lump clay, and finally, at a depth of 30 to 35 feet, stratified sand and silt.

GAS EMANATING FROM THE MUD LUMPS.

Gas escapes at many places on the surface of the Delta, the vents appearing to be most numerous and largest on and near the mud lumps, though the rate of flow rarely, if ever, exceeds a few cubic feet an hour. Gas rises in bubbles in all the mud springs, though its rate of issue varies. It also escapes from many cracks in the mud, rising bubbles being noticeable in many places in the shallow water around the lumps.

Two samples of gas were collected from the mud springs and on analysis were found to consist principally of marsh gas (CH_4), mixed with some oxygen, nitrogen, and carbon dioxide.[1] Other samples have been collected by E. W. Hilgard and A. L. Metz, and the analyses given by them show similar results, except that Hilgard reports no oxygen.

The results of the analyses are believed to show correctly the general composition of the gas, at least at the particular vents where the samples were taken. They appear to indicate that the gas is not of deep-seated origin but has developed within a few feet of the surface, for it lacks certain hydrocarbons commonly present in gas found deep in the earth. The principal constituent, methane (CH_4), emanates from most if not all marshes and generally carries with it minor and variable amounts of nitrogen, oxygen, and carbon dioxide, all of which are produced in the decay of vegetable matter. Hence it appears probable, though not certain, that the gas from the mud lumps is produced in the ordinary reduction process which affects plant material in marshes.

CONCLUSIONS.

The facts that the mud lumps are by far the thickest bodies of clay found in the Delta and that the clay is overlain and underlain by materials similar to those found elsewhere throughout the lower end of the Delta suggest that they are produced by a squeezing of the soft layers and an accumulation of clay from such layers in places where the pressure is less strong, and that the lumps are not upheaved by any such force as volcanism or by pressure from the accumulation of salt, sulphur, or gas below the surface.

The reasons for believing that the mud lumps are not of gaseous origin may be summarized as follows: (1) Their growth does not increase rapidly and terminate with something like an explosion through which the gas pressure is relieved. (2) Numerous borings which have recently been made have penetrated apparently to the bases of the lumps (to layers of sandy and clayey silt like those found elsewhere throughout the Delta), without opening any considerable gas reservoirs. (3) The lumps are somewhat closely associated with the ends of the passes and there would seem to be no reason for this association if they were due to gas pressure. (4) The more fluid clayey layers are greatly thickened instead of thinned in the upheaval. (5) The gas given off is small in amount. (6) The lumps seem to reach equilibrium when they rise to sea level or a few feet above. If they were due to gas they would presumably not be concordant in height.

Hilgard's idea concerning the origin of the lumps—namely, that they are produced by the pressure of a heavy resistant layer upon a fluid layer below—appears to be in accord with some of the facts, but the results of borings recently made do not appear to support it, because, so far at least, no layer of fluid material has been found below the surface, but instead alternating thin layers of somewhat stiff sand and somewhat fluid clay. The process of flocculation by salt water is no doubt continually in progress, but the small percentage of clay in the sediment, the seasonal changes, and the work of littoral currents appear to prevent the accumulation of a thick body of semifluid clay. Another point in Hilgard's theory which seems open to question is his idea that the lumps rise where the current has scoured to a greater depth than before existed, thus weakening the crust of silt. (See Pl. II.) The mud lump in South Pass Channel to which he refers and also the lumps in Southwest Pass are beyond the ends of the jetties, where the bottom instead of being scoured deeper has been silted up.

The results of the recent work, though considerably more extensive than was hoped from an investigation covering so short a time, are meager. The inferences as to the significance of the data so far gathered may be incorrect, and new work may lead to conclusions very different from those which now seem most reasonable. For example, it may be found that at a depth of 50 feet or more the material is quite different from that which has so far been penetrated, that it is more fluid, and that it has played the most active part in mud-lump growth.

The new hypothesis, which seems better favored by the data now in hand than any other, is that the mud lumps are produced by a gentle seaward flow of layers of semifluid clay under the land and the shallow water near the ends of the passes, where this flow is opposed by the comparatively resistant parts of the foreset beds. The tendency to flow is assumed to be due to pressure developed by constant additions of sediment. Between the passes, where the material is clayey and very yielding, this flow may reasonably take place without much upward buckling anywhere, but near the ends of the passes, where wave and current action sort the sediment and carry away some of the fine particles, leaving the more resistant material, the material is more sandy and resistant. Also there is a greater lack of equilibrium between the heavy land on the one side of a well-defined line and the water—only about half as heavy—on the other than there is between the passes, where the angle between the top and front of the Delta is not nearly so well defined. It seems reasonable to suppose that in places along the border between the comparatively resistant and steeply dipping parts of the foreset beds and the clay-bearing beds toward the land the pressure may be relieved by upward buckling accompanied by great thickening of the clay. Such phenomena are not rare. The flowage of semifluid clay has been frequently observed. It sometimes causes great difficulty in railway building or gives rise to surprising changes in swamps. The unequal and intermittent settling of jetties, though they are well founded on large willow mattresses, also suggests squeezing and flowage. This settling has caused the abandonment of concrete for jetty building and a return to the use of large blocks of crushed stone. The mud lumps appear to be the product of flow, because in no other places have such thick bodies of clay been found, and the facts that they occur almost exclusively near the ends of the passes—most commonly west of them, where probably the principal part of the sediment is being deposited—and that they are most active during and after times of high water seem to be in accord with the hypothesis here presented.

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[1] Shaw, E. W., Gas from mud lumps at the mouths of the Mississippi: U. S. Geol. Survey Bull. 541-A, pp. 12-15, 1913.

The full details of the process will probably not be known until much more field work has been done. Perhaps if the origin of the mud lumps can be learned, their formation in places where they are objectionable may be prevented by shifting the locality of deposit or by modifying in some way the distribution of the sediment. The fact that other large deltas are without mud lumps appears to offer encouragement that a solution of the problem may be found.

INTERPRETATION OF ANOMALIES OF GRAVITY.

By Grove Karl Gilbert.

THE ANOMALIES.

A by-product of the adjustment of primary triangulation for the United States was the determination of the deflection of the vertical at 765 stations.[1] In discussing these deflections Hayford introduced the hypothesis of isostatic compensation, with the result that the deflections were "thereby reduced to less than one-tenth of the mean values which they would have if no isostatic compensation existed." [2] The particular form given to the hypothesis was this: At some depth below the horizon of sea level, called the *depth of compensation*, the stresses due to gravity are uniform. Each unit vertical column above the horizon of compensation contains the same mass,[3] the product of the length of the column by its mean density being the same in all places, or the variation of length associated with topographic relief being compensated by reciprocal variation of mean density. In the adjustment of the deflections of the vertical various assumptions were made as to the depth at which compensation is complete, and the depth yielding the best adjustment was found to be 122 kilometers.

Hayford and Bowie, in discussing the determinations of gravity at stations in the United States, used the same hypothesis of isostatic adjustment and adopted from Hayford's earlier work the estimate of 122 kilometers as the depth of compensation. For each of 124 stations at which the intensity of gravity had been measured they computed the attractive influence not merely of the elements of the neighboring topography, but of the topographic elements of the entire earth, and the whole computation was made subject to the isostatic hypothesis. The attractive influence thus deduced was added (algebraically) to the value of gravity appropriate to the latitude and altitude of the station, giving a theoretic or computed value, which was then compared with the value obtained by observation. The difference observed minus computed—is called the local anomaly of gravity. The mean of the 124 anomalies is 0.020 dyne. This is approximately one-fourth as large as the mean of anomalies obtained without the introduction of the isostatic hypothesis.

The success of the hypothesis in reducing anomalies of the vertical and anomalies of gravity is held—properly, as I think to show that isostatic adjustment in the earth's crust is nearly perfect. Taking the outstanding or residual anomalies as measures of the approximation to perfect adjustment, the authors state that the mean anomaly in the vertical corresponds to the mass of a rock layer 250 feet thick, and the mean anomaly in gravity to a rock layer 630 feet thick.[1]

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[1] The papers to which the present article refers are as follows:

Hayford, J. F., The figure of the earth and isostasy from measurements in the United States, U. S. Coast and Geodetic Survey, Washington, 1909; Supplementary investigation in 1909 of the figure of the earth and isostasy, U. S. Coast and Geodetic Survey, Washington, 1910; The relations of isostasy to geodesy, geophysics, and geology, Science, new ser., vol. 33, pp. 199-209, 1911.

Hayford, J. F., and Bowie, William, The effect of topography and isostatic compensation upon the intensity of gravity, U. S. Coast and Geodetic Survey Special Pub. No. 10, Washington, 1912.

Bowie, William, Effect of topography and isostatic compensation upon the intensity of gravity, U. S. Coast and Geodetic Survey Special Pub. No. 12, Washington, 1912; Some relations between gravity anomalies and the geologic formation[s] in the United States, Am. Jour. Sci., 4th ser., vol. 33, pp. 237-240, 1912.

Spencer, J. W., Relationship between terrestrial gravity and observed earth movements of eastern America, Am. Jour. Sci., 4th ser., vol. 35, pp. 561-573, 1913.

[2] Figure of the earth and isostasy, p. 175.

[3] Mass is the term employed by Hayford, and his usage has been followed in the present paper. In strictness weight is the quantity with which isostasy is concerned, and the substitution of mass for weight in the analyses involves the assumption that gravity is uniform from top to bottom of the zone of compensation. It is, in fact, about 1 per cent greater at the depth of 122 kilometers than at the surface. The numerical errors possibly entailed by the substitution are negligible.

Each measurement of the intensity of gravity is of course affected by an error. The corresponding computed intensity is also affected by an error. Their difference, the anomaly, is the algebraic sum of the two errors. The average error of the observed values of gravity is demonstrably small, so that the anomalies differ little from the errors of the computed values. The error of a computed value is not all from a single source. Part of it comes from the data used, such as the altitude, the mean density of the surface rock, and especially the configuration of the surrounding topography; another part comes from the methods of computation, which were somewhat shortened for the sake of economy; and a third part comes from assumptions connected with the specific hypothesis of isostatic compensation. The authors cited discuss these classes of error with care and reach the conclusion that all are small in comparison with those arising from the assumptions.[2] An attempt to interpret the anomalies may therefore properly include the consideration of their relations to various assumptions.

INTERPRETATION BY IMPERFECT ISOSTATIC ADJUSTMENT.

The explicit general assumption as to compensation is that the excess of mass in any crustal column due to its projection above sea level is exactly compensated by defect in density uniformly distributed from the surface to a depth of 122 kilometers; and that defect of mass in any unit column beneath the ocean is similarly compensated by excess of density (with due allowance for the mass of the overlying water). This general assumption includes the more specific assumptions (1) that the compensation is perfect, (2) that the compensatory defect or excess is uniformly distributed through the column, (3) that the depth of compensation, 122 kilometers, is not subject to variation from place to place. To these may be added an implicit assumption of which there will be occasion to speak on a later page. The inexactness of the three assumptions is explicitly and fully recognized by the authors cited,[3] but their discussion gives prominence only to the inexactness of the first. In a general way they interpret the anomalies as due to uncompensated local excesses or defects of mass in the crustal layer, or, in other words, to imperfection of isostatic adjustment. The present paper will consider the possibilities of interpretation connected with the other specific assumptions.

INTERPRETATION BY VERTICAL HETEROGENEITY OF CRUST.

In place of the assumption that the vertical distribution of compensatory density difference is uniform, let us assume that it is subject to the same variation as is the assumed horizontal distribution of compensatory density difference. In each case the compensatory element of density is but a small fraction of the entire density.

The topographic relief most intimately associated with the gravity stations is that of the United States. The mean altitude of the United States, as given by the authors, is 2,500 feet, or 762 meters; and the compensatory correction to density for +762 meters is $-\frac{762\times 2.67}{122{,}000}=-0.0167$. The compensatory correction for neighboring oceanic topography is positive, and its average is coordinate in amount. The value 0.0167 may serve as a rough estimate of the average departure in density which was assumed in computing corrections for topography. An alternative estimate may be based on the topographic relief of the entire globe. Again, using the level of the ocean surface as a horizon of reference, making due allowance for the partial compensation given by the mass of the water, and combining positive and negative corrections irrespective of sign, we have 0.0381 as the resulting value of the average departure in density. Neither mode of estimation is entirely satisfactory, but together they yield an order of magnitude; and an intermediate value, 0.025, will be accepted as sufficiently precise for the present purpose. In order to discuss the effect of a vertical variation of density coordinate in amount with the postulated horizontal variation, it will be assumed that the average deviation of the density of any large portion of the crustal column from its normal is 0.025.

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[1] This figure applies to 122 instead of 124 anomalies. By omitting two aberrant anomalies the mean is reduced from 0.020 to 0.018. See Special Pub. No. 12, p. 23.

[2] Special Pub. No. 10, pp. 88–94.

[3] Idem, p. 11.

In the diagram, figure 7, vertical distance represents depth below the earth's surface, *A* corresponding to the surface and *B* to the level of compensation, 122 kilometers below. Horizontal distances, measured from *AB* as origin, represent density. The line *CD* arbitrarily represents the normal curve of density in relation to depth. The nature of the curve within the zone of compensation is unknown, and its form has no importance in the present connection. The shaded area *CE* expresses the assumption that in a particular locality the upper half of the zone is characterized by a uniform defect of density, and the shaded area *DF* expresses the assumption that in the same locality the lower half of the zone is characterized by an excess of density of the same amount. The widths of the areas correspond by scale to departures of 0.025. The introduction of these departures in density does not affect the total mass of the unit column, but it does affect the intensity of gravity at the top of the column. The tract of deficiency being nearer to the surface than the tract ot excess, the loss of attraction exceeds the gain and there is a net reduction of the intensity of gravity.

To obtain numerical results it is necessary to assume horizontal as well as vertical dimensions for the bodies of rock affected by abnormality of density, and computations are facilitated by giving each ideal body the form of a right cylinder, the one resting on the other. The radius of the cylinders is assumed as 61 kilometers (one-half of the depth of the level of compensation); the assumed defect in density for the upper cylinder and the assumed excess for the lower are each 0.025; and the station on which their influence is computed is assumed to be at the center of the upper face of the upper cylinder. The computed influence [1] of the defect in density on gravity at the station is −0.0375 dyne; that of the excess is +0.0115 dyne; and their algebraic sum is −0.026 dyne. If the excess of density is in the upper body and the defect in the lower, the effect on surface gravity is +0.026 dyne. These quantities are to be compared with the mean anomaly for the system of gravity stations, which is 0.020 dyne.

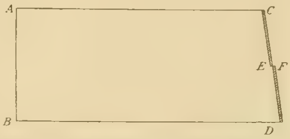

FIGURE 7. Hypothetic relation of density anomalies to densities and to depths.

Thus it appears that the same moderate assumptions as to variation of density which Hayford and Bowie apply to horizontal relations in discussing isostatic compensation yield, if applied to vertical relations, departures in gravity intensity of the same order of magnitude as the outstanding anomalies found after making allowance for isostatic compensation. From this I infer that the anomalies may be in part due to irregularities in the vertical distribution of densities, or that such irregularities are competent, alike in the nature of their influence and in its possible amount, to cause such anomalies of gravity as have been discovered.

INTERPRETATION BY VARIATION OF DEPTH OF COMPENSATION.

Let us now consider the effect of removing the restrictive assumption which makes the depth of compensation uniform at all points. In Hayford's discussion of deflections of the vertical separate computations are made for ten divisions of the United States, and the results of these computations lead to the conclusion "that while there are indications that the depth of compensation is greater in the eastern and central portions of the United States than in the western portion, the evidence is not strong enough to prove that there is a real difference in depth of compensation in the different regions;" [2] but the authors of the papers on gravity use only the assumption of uniformity. In view of the recognized heterogeneity of crustal material it appears to me both possible and probable that the depth at which material is sufficiently mobile to effect isostatic adjustment is subject not only to regional but to highly localized variation. To obtain an idea of the quantitative relations between local variation of the depth of compensation and resulting variation of gravity, I have postulated a circular tract having a radius of 61 kilometers and having such topographic relief that the compensatory density, for a depth of 122 kilometers, is −0 025. Then I have introduced various changes in the postulated depth of compensation, with corresponding changes in the compensatory density, and computed the effect on local gravity. The change in intensity of gravity corresponding to 40 per cent increase in the depth of compensation is −0.0161 dyne; the change corresponding to 40 per cent decrease is +0.0125 dyne. These quantities are to be compared with the mean anomaly of gravity, 0.020 dyne. The resulting figures would be somewhat but not greatly different if the computations were applied to an area several times larger.

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[1] Computed by means of a formula given by Hayford and Bowie in Special Pub. No. 10, p. 17.

[2] Figure of the earth and isostasy, p. 143.

The general fact appears to be that local variations of the depth of compensation are competent to cause anomalies of gravity, but that very large variations would be necessary to produce such anomalies as have been observed. To explain in this way the greatest of the anomalies it would be necessary to assume that the zone of compensation is many times as deep at some places as at others. While such a condition may not be impossible, the geodetic results indicate that it is highly improbable; and I am disposed to regard variation in depth of compensation as decidedly less available in interpreting anomalies than variation in the vertical distribution of densities.

GEOLOGIC RELATIONS OF ANOMALIES.

To exhibit the geographic distribution of anomalies the authors cited have drawn lines of equal anomaly on a map of the United States;[1] and these lines are reproduced in Plate IV. The contour interval is 0.01 dyne, and areas of plus anomaly are distinguished from areas of minus anomaly by shading. The positive and negative anomalies are not indiscriminately mingled, as should be expected if the anomalies had the character of accidental errors, but fall into groups. Large districts of plus anomaly appear and other large districts of minus anomaly. This effect is undoubtedly heightened by the fact that the distances between stations are large, but is not created thereby. A comparison of parts of the map controlled by numerous stations with parts controlled by few and a comparison of this map based on 124 stations with an earlier map based on 87 stations leave no question in my mind that there is a veritable areal grouping of the anomalies. With the multiplication of gravity stations the courses of the lines will be modified, and contrasted areas will become more clearly defined, but the type of the future map is shown by the one we now have.

The anomaly map is in some way an expression of subterranean structure, for it tells of the distribution of mass. As the subterranean structure is a product of the earth's history, the distribution of anomalies has a historical significance. To determine the nature of this significance is a problem in interpretation.

Bowie[2] has classified the anomalies according to the geologic formations occurring at the stations to which they pertain, thus in effect attempting a correlation between the map of anomalies and the geologic map, but the correspondences are not important. By a series of computations he shows that such local excesses or defects of mass as may be ascribed to the densities and volumes of formations visible at the stations are not at all adequate to explain the anomalies.

Hayward and Bowie have compared the anomalies with areas of large recent unloading of the crust by erosion and with areas of large recent loading by deposition, but have not found such correspondence as to support the hypothesis of cause and effect;[3] and a similar negative result followed an attempt to correlate anomalies with the loadings and unloadings of certain districts by the ice of glacial time.[4] Spencer[5] emphasizes the fact that there are large plus anomalies within the region once covered by the Laurentian ice sheet and regards it as proof

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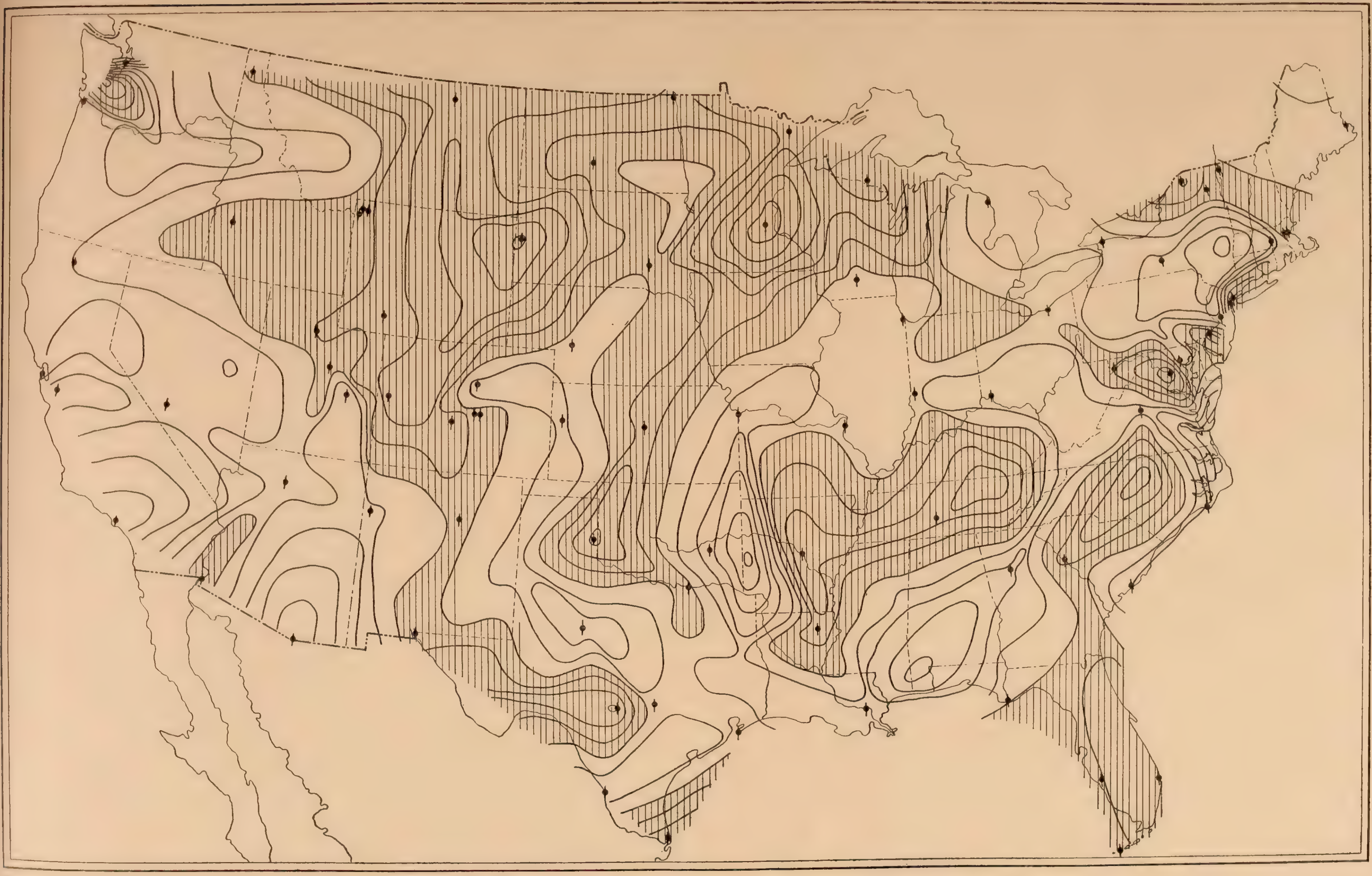
[1] Special Pub. No. 12, illustration No. 2.

[2] Am. Jour. Sci., 4th ser., vol. 33, pp. 237-240, 1912. See also U. S. Coast and Geodetic Survey Special Pub. No. 10, pp. 113-117, 1912.

[3] Special Pub. No. 10, p. 112.

[4] Idem, p. 116.

[5] Am. Jour. Sci., 4th ser., vol. 35, pp. 569-570, 1913.



MAP OF THE UNITED STATES SHOWING LINES OF EQUAL ANOMALY OF GRAVITY.

Areas of plus anomaly are shaded. Contour interval, 0.01 dyne. Gravity stations are indicated by dots.

that the rising of that region after the removal of the ice load was not caused by the removal of load.

In the drawing of inferences from the relations of anomalies to loading and unloading much depends on the mode of interpreting anomalies; and, conversely, the relations of anomalies to loading and unloading may be used as tests of modes of interpretation. In a general way the continental shelves have long been areas of loading and adjacent land districts have been areas of unloading. To whatever extent isostatic compensation for this loading and unloading has been imperfect, to whatever extent the readjustment lags behind the disturbance of equilibrium, there should be an excess of mass under the submerged shelf and a deficiency under the land. Under the hypothesis of interpretation which correlates excess of mass with plus anomalies and defect of mass with minus anomalies we should expect to find, as a general fact of the anomaly map, an anomaly gradient from ocean to land in coastal regions. Such a gradient is, in fact, found between Boston, Mass., and Trenton, N. J., and between Florida and the Rio Grande, the two stretches comprising one-third of our coast; but the gradient is unequivocally oceanward between Delaware and Florida; and elsewhere its direction is parallel to the coast. The Appalachian belt south of the region of glaciation has been practically free from loading during two geologic ages and has been unloaded to the extent of many thousands of feet of rock. Isostatic adjustment may be supposed to have added mass in compensation for the unloading, or for part of it, but may not plausibly be supposed to have overcompensated so as to create an excess of mass. Nevertheless, there are large plus anomalies in that belt, and their existence evidently creates a difficulty in interpreting plus anomalies as due to crustal excess of mass. The district of greatest loading in recent time is the Delta of the Mississippi, and if isostatic adjustment has not fully kept pace with the loading there should be in this district a local excess of mass. The fact that the local anomaly is minus instead of plus calls in question the mode of interpretation which infers crustal defects of mass from minus anomalies.

The hypothesis that certain Pleistocene sinkings and risings of the land were caused by the associated additions and removals of ice load is in general accord with the theory of isostatic adjustment. If it is true that the crust became approximately adjusted to the last loading and that the subsequent deformation, of which we have record in the inclined shores of glacial lakes, was caused by a readjustment during and after the final unloading, then there should be no excess of mass in the readjusted or readjusting area. Because there is a tract of plus anomaly within this area Spencer discredits the hypothesis of deformation through unloading, but the fact may equally be used to discredit the hypothesis underlying his mode of interpreting anomalies.

In all these cases involving loading or unloading the hypothesis that the anomalies represent imperfect compensation and imperfect adjustment yields results which are unsatisfactory because they are opposed to plausible expectation, and the expectation is plausible because it is founded on the theory—we need no longer call it the hypothesis—of isostatic adjustment. In all these cases the distribution of anomalies may be reconciled with rational expectation by assuming local irregularities in the vertical distribution of densities, and the irregularities thus assumed need be only of the order of magnitude of those irregularities in horizontal distribution of densities which have been assumed in the reduction of the geodetic observations.

In my opinion these considerations connected with phenomena of loading and unloading serve to show that the anomalies may not properly be interpreted as due exclusively to crustal excesses and defects of mass existing because of imperfection of isostatic adjustment. Some additional mode of interpretation must be admitted, and at least one other mode, that connected with irregularities in the vertical density gradient, appears to be both qualitatively and quantitatively competent.

If the two modes of interpretation are accepted as coordinate, it becomes possible to extend the conclusion of Hayford and Bowie as to the perfection of isostatic adjustment. The one mode of interpretation, if used exclusively, yields an average imperfection of adjustment measured (positively or negatively) by the weight of a layer of rock 630 feet thick; the other, if used exclusively, implies no imperfection of adjustment. Any combination of the two yields the conception of an adjustment more nearly perfect than would be implied by the measure of 630 feet of rock.

If vertical irregularity of density were to be accepted as the exclusive cause of gravity anomaly, the map of gravity anomaly would become (approximately) a map of vertical density anomaly, each area of minus gravity anomaly being replaced by an area in which departures from the normal density gradient of the crust are negative near the surface and positive below and each area of plus anomaly by one in which density departures are positive near the surface and negative below. Such a change would remove the problem of interpretation to a new position, by raising the question of the origin of the anomalies in density. Giving attention to this new question, I have been led to the suggestion that a competent cause for the peculiarities of density distribution would be apt to find expression also in the greater facts of the structure of the continent. Among those greater facts, so far as we are able to read them in the visible structure and physiography, are (1) the Appalachian-Ozark belt of corrugation and (2) the strong contrast, farther west, between a cordilleran region of strong orogenic disturbance and a plains region of relative freedom from disturbance; and I have studied the relation of these features to the features of the anomaly map. The correspondences are so slight that they may be regarded as accidental, and the general relation is that of independence and discordance. The result is of limited significance because the visible structure elements may constitute but a small fraction of the structure of the crust, but so far as it goes it fails to support the hypothesis that the anomalies of gravity are due exclusively to anomalies in the vertical distribution of density within the crust.

THE LOCUS OF ADJUSTMENT.

Hayford has given an analysis of the general mechanics of isostatic readjustment when the isostatic equilibrium has been disturbed by erosion and deposition.[1] The analysis reveals stresses tending to cause an undertow within the crust, and adjustment is ascribed by Hayford to the undertow. My own conception of the process of adjustment accords with these features of his analysis, but adds the idea of relative mobility as an important condition in determining the place of underflow and the perfection of the adjustment.

Now that the argument from tides has been efficiently supported by that from the speed of earthquake waves, we may accept with confidence the doctrine of the high rigidity of the earth's nucleus. The theory of high rigidity accords also with the fact of high density, provided the nucleal materials are similar to the crustal, for with sufficient compression the viscosity of even the most mobile fluids become high rigidity. Immobility at all depths below that of compensation is either explicitly or implicitly assumed by Hayford and Bowie.

On the other hand, there is much geologic evidence of mobility somewhere below the surface. Part of this evidence is volcanic. The continuous or secular relations of pressure, temperature, and density in the subterranean region from which liquid rock rises at intervals may be assumed to be such that moderate change of condition either induces liquefaction or else so lowers the density of rock already liquid as to render it eruptible; and such a balancing of conditions implies some sort of mobility. Other evidence is diastrophic. In some regions, such as the Appalachian, overthrusts and folds testify to great reduction in the horizontal extent of rocks near the surface, the reduction having been accomplished in a small fraction of geologic time. If the subjacent portion of the nucleus had been correspondingly forced into narrower space there would have resulted an enormous mountain range, but the actual uprising was of moderate amount. Plausible explanations of the phenomena necessarily include horizontal movements of the upper rocks without corresponding movements of the nucleus and thereby imply mobility in an intervening layer. In certain block-mountain districts of the West the master faults are antithetic in type to the overthrust and demonstrate pronounced extension of the upper part of the crust. The nucleal tract beneath could not share in this extension without creating an enormous depression, which does not exist; and the interpretation of the phenomena involves horizontal shear in material more mobile than the visible upper rocks.

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[1] Science, new ser., vol. 33, p. 202, 1911.

The conception thus engendered, of a relatively mobile layer separating a less mobile layer above from a nearly immobile nucleus, appears to me in full accord with the evidence which geodesy affords of isostatic adjustment. The geodetic "depth of compensation" agrees with such suggestions as to the position of the horizon of maximum mobility as might be afforded by the volcanic and diastrophic phenomena. The existence of a horizon of mobility accords with the inference of approximate perfection of isostatic adjustment.

It is not necessary to suppose that the degree of mobility at the horizon of mobility is that of a liquid at the surface. When such mobility is attained by any but the densest rocks eruption takes place. It is not necessary to think of the degree of mobility as uniform, either from place to place or from time to time. Its place variation would naturally be coordinate with that of rock types, and its time variation coordinate with epochs of elevation and subsidence. Neither should the depth of the horizon of maximum mobility be thought of as uniform.

INTERPRETATION BY NUCLEAL HETEROGENEITY.

The inner earth is the inalienable playground of the imagination. Once it contained the forges of blacksmith gods; or it was the birthplace of our race, or the home or prison of disembodied spirits. Later Symmes hollowed from it a vast habitable empire, concave like the world of Koresh. Science now claims exclusive title but holds it chiefly for speculative purposes; and the freedom of speculation practically recognizes but two limitations: The inner earth is dense, and it is rigid. As to all other properties opinion is untrammeled.

It is my own view that the inner part of the nucleus is not merely hot, but very hot. If the law of compression by pressure and the law of expansion by heat, as we know them at the surface, apply equally to the nucleus, then the mean temperature of the earth must be enormous in order to afford a mean density so low as 5.6. An enormous temperature implies an enormous store of heat. This is the source of the energy involved in the hypogene activities of the earth, and it is fed to the crustal region by conduction. If the earth were composed of homogeneous shells diversity of crustal activity would depend on outside conditions only and would be connected with latitude. In fact, however, the diversity of crustal activity is largely independent of latitude. It is in part related to visible diversity of crustal material, but in larger part it appears unrelated to things visible. Deformation sometimes shows or seems to show dependence on erosion and deposition, but any such scheme of causation yields a running-down process and fails to account for the perpetual initiative of geologic activity through the ages. The deformations which have not only developed but perpetually remodeled the continents have a source below the surface. Their method probably involves reactions between temperature, pressure, and the physico-chemic constitution of rocks, but these reactions, like the superficial reactions, yield running-down processes and do not afford a fundamental explanation of crustal activity. The factor to which I appeal is primordial heterogeneity of earth material, a heterogeneity which gives diversity to the flow of heat energy and to the physical and chemic changes of crustal regions. It does not seem sufficient that the crust be heterogeneous; there should be heterogeneity also below the horizon of mobility.

Under this speculative view of the earth's constitution the anomalies of gravity may be in part occasioned by tracts below the level of compensation which are characterized by exceptional density. It appears to me quite possible that underflow in a mobile layer might effect a practically perfect adjustment for differences in density above the layer, so as to bring crustal densities and crustal relief into harmony, and yet leave uncompensated the differences in density of the nucleus.

To obtain some idea as to the quantitative ability of nucleal heterogeneity to modify gravity, let us assume that abnormalities of density are as great in the nucleus as in the crust. Let us assume that just below the horizon of compensation is a nucleal tract in which the abnormality of density is ±0.025, and that the form and dimensions of the tract are those of a right cylinder with height and radius each equal to 122 kilometers. The computed attraction of the nucleal abnormality of mass, exerted at a gravity station situated directly above the center of the cylindric tract, is ±0.023 dyne; and this is of the same order of magnitude as the mean anomaly of gravity, 0.020 dyne. The influence of such an abnormality of mass would have its maximum at the station and would diminish with increasing distance from the station, the general result being a hill or a hollow on the contour map of anomalies of gravity.

The mode of interpreting gravity anomalies which appeals to nucleal heterogeneity is applicable not only to those anomalies which encounter difficulty in dealing with districts of loading and unloading, but also to those grouped anomalies whose areas and contours exhibit independence of all visible geologic structure. It seems, in fact, to be competent to account for all anomalies except such as exhibit very steep gradient. On the other hand, if the development of the subject shall show that there are anomalies which can be explained in no other way, the existence of such anomalies may constitute evidence of nucleal heterogeneity.

Hayford and Bowie, by ignoring the possibility of nucleal density anomalies, implicitly assume isostatic adjustment in the nucleus, such an adjustment as would exist in a nucleus composed of concentric homogeneous shells. The alternative interpretation of gravity anomalies just outlined is founded on the supposed inexactness of that assumption.

REVIEW AND CONCLUSION.

The mean density of the earth is about twice the average density of earth material at the surface. In a general way density increases from the surface downward. If the density gradient were everywhere the same the earth might be described as composed of concentric layers, each homogeneous as to density. The actual departures from such an equable arrangement may be called anomalies of density. Anomalies of density systematically related to topographic relief have been assumed by Hayford and Bowie in computing theoretic gravity at each gravity station, the difference between the theoretic gravity and observed gravity being the local anomaly of gravity. An anomaly of gravity (except as affected by errors of observation, etc.) is caused by anomalies of density other than those systematically introduced into the computations. Hayford and Bowie's system of density anomalies is one which assumes isostatic equilibrium at a depth of 122 kilometers. The distribution of the additional anomalies of density necessary to account for the anomalies of gravity is unknown. So many different distributions seem possible that the actual distribution may not be determinable. One suggested distribution (Hayford and Bowie) includes only horizontal variation and restricts variation to the crustal region. It involves moderate imperfection of isostatic equilibrium at the depth of 122 kilometers, and it encounters difficulties when applied to the anomalies of regions which have recently gained or lost mass through loading or unloading. A second suggested distribution, or element of distribution, involves vertical variation within the crustal region. Taken by itself it seems equally competent with the first, and it does not involve the same imperfection of isostatic equilibrium. A third suggestion, coordinate with the others in that it is quantitatively adequate, is that the additional anomalies of density are not confined to the crustal region but occur also at depths greater than 122 kilometers and below the region of isostatic adjustment. A fourth suggestion, that the distribution of the additional anomalies of density is connected with variation in the depth of the horizon of adjustment, may supplement either of the others but is not by itself sufficient to account for the anomalies of gravity.

Volcanic phenomena and phenomena of crustal shortening and crustal extension indicate a horizon of relative mobility above the rigid nucleus. To whatever extent a subcrustal layer is mobile the means are furnished for approximately perfect isostatic adjustment at that level. It is inferred that the actual adjustment is more nearly perfect than would be indicated by the geodetic data if those data were interpreted according to the first of the above-mentioned suggestions. The geologic evidence in favor of a mobile layer combines with the evidence from approximate isostasy despite surface transfers of load to show that the anomalies of gravity are not due chiefly to uncompensated excesses and deficiencies of mass in the crust; and I incline to the view that the hypothesis which so interprets them is one of the least probable of the four suggested.

The second and third suggested interpretations—that by vertical arrangements of anomalies of density within the crust, and that by anomalies of density below the horizon of isostatic adjustment—are not competitive, and each may prove to have its field of application. The second has a sound basis, for vertical variation of density in the crust is demonstrated as far down as the sources of volcanic eruption. The third has perhaps no more than a presumption in its favor. The failure of anomalies of gravity to group themselves in harmony with large features of crustal structure makes it easy to think that their grouping may be related to nucleal structure. When the multiplication of gravity stations shall have relieved some of the broad areas of the anomaly map from their present vagueness, the groupings may be found more significant than they seem at present. Crustal diversity may be to an important extent a product and record of the geologic chapter of earth history. Nucleal diversity, if it exists, belongs to pregeologic chapters.

Starting with geodetic and topographic data and assuming certain uniformities, Hayford and Bowie have demonstrated isostasy and developed a gravity anomaly map. The map contains a body of observational data coordinate with the geodetic and topographic. By a future mathematical discussion which treats the three bodies of data together and which recognizes alternative interpretations of the anomalies of gravity it may be possible to practically demonstrate the meaning of the anomaly map. At present the map seems to express chiefly an effect of heterogeneity in the nucleus and an effect of irregularity in the vertical distribution of densities within the crust.

THE JURASSIC FLORA OF CAPE LISBURNE, ALASKA.

By F. H. Knowlton.

INTRODUCTION.

A peculiar and absorbing interest attaches to the study of the fossil floras of the arctic regions, for they indicate climatic conditions very unlike those now existing in those regions. In place of the present snow and ice and the scant, almost perpetually frozen soil which supports but a handful of depauperate plants, the conditions from at least late Paleozoic to middle Cenozoic time made an abundant and luxuriant vegetation possible, at least during certain periods. Although these lands are now so inhospitable, and hence but rarely visited, an astonishing amount of information concerning their fossil floras has been accumulated, and to this knowledge Alaska has contributed its full quota, though doubtless much more will ultimately be known.

The recent publication of a report by Prof. A. C. Seward on the Jurassic plants of Amurland, long known from the historic researches of Oswald Heer, has called to mind the existence of a considerable collection of similar plants from the vicinity of Cape Lisburne, Alaska, that has been in my possession for a number of years. As it is now possible, with Seward's paper in hand, to recognize still further the striking resemblances between the Jurassic floras of Alaska and Siberia, it seems an opportune time to present the results of this recent study. A preliminary examination of this material was made, and certain tentative identifications were adopted in a short report for the use of the geologists who collected it, but this is the first time it has been adequately described and figured.

The material considered in this paper was collected in 1904 by Arthur J. Collier, of the United States Geological Survey, while engaged in a study of the geology and coal resources of the Cape Lisburne region.[1] The coal deposits are extensive and are the only mineral resources of the region known to be of commercial importance. Collier describes the locality as follows:

> Cape Lisburne is the bold headland which marks the northwestern extremity of a land mass projecting into the Arctic Ocean from the western coast of Alaska between latitudes 68° and 69°. It lies 160 miles north of the Arctic Circle, about 300 miles directly north of Nome, and is the only point in Alaska north of Bering Strait where hills above 1,000 feet in height approach the sea.

So far as known, the rocks of the Cape Lisburne region are all sedimentary. The ages represented, with the approximate thickness of each, is given by Collier as follows: Devonian (?), 2,000+ feet; Lower Carboniferous [Mississippian], 4,500+ feet; Upper Jurassic, 15,000+ feet; Lower Cretaceous (?), 10,000+ feet; Pleistocene, 50 feet.

THE CORWIN FORMATION.

The Jurassic section to which the name Corwin formation has been given is described by Collier [2] as follows:

> The older of the Mesozoic formations, which takes its name from Corwin Bluff and the coal mines there located, is best exposed on the coast at a point 26 miles east of Cape Lisburne and thence extends northeastward to Cape Beaufort, a distance of 40 miles, which is the limit of this investigation. It is known to occur again near Wainwright Inlet

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[1] U. S. Geol. Survey Bull. 278, pp. 1 54, Pls. I IX, 1906.

[2] Op. cit., p. 27.

> 100 miles beyond Cape Beaufort, and there is some reason for the belief that it is continuous to that point. The southern boundary of the formation extends in a southeasterly direction from the coast for about 12 miles, when it turns to the south. Beyond this the inland extension of the formation has not been determined. * * *
>
> No contact between the Corwin formation and the Carboniferous [later determined to be in part Triassic] rocks described occurs within the limits of the area under investigation, though an unconformity is evident from certain beds of conglomerate containing pebbles derived from the Carboniferous. Lithologically the formation consists of rather thinly bedded shales, sandstones, conglomerates, and coal beds. Fossil plants occur in the shales wherever they have been closely examined. * * * The formation throughout presents very little variation in lithologic character beyond the fact that in some portions of the section the shales are more carbonaceous, while in others they are more calcareous. Throughout the section there is nearly the same proportion of sandy beds.

As already indicated, the Corwin formation reaches the enormous thickness of over 15,000 feet and contains forty to fifty coal beds which range in thickness from 1 or 2 to over 30 feet, ten being over 4 feet thick and suitable for mining, the whole aggregating at least 150 feet.

PLANT COLLECTIONS.

The plant material obtained from the Corwin formation is comprised in nineteen collections, from as many localities, distributed along the coast from Corwin Bluff to Cape Beaufort, a distance of about 140 miles and apparently representing beds at different horizons throughout the formation. So far as the data at hand indicate, there is little or no variation in the flora through the whole thickness of the formation. When the preliminary examination of this material was made, and without knowing the relative stratigraphic position of any of the collections, a tentative attempt was made to fix the position in the section of a few of the lots. This attempt, however, was a failure, for certain collections which it seemed probable belonged near the base were in reality well distributed through the section and, for the present at least, the flora must be considered as a unit. As Collier has well said, "It is reasonable to expect some changes in the flora from the base to the top of a formation of such great thickness, but in this case the variation, if it exists, will probably be detected only by the paleobotanist after a critical personal examination of the section."

As Collier's collection was not the first to be made in the Cape Lisburne region, a brief review of previous collections and the age determinations given to them may be of interest.

Apparently the first to obtain material from the Corwin formation was A. Collie, who accompanied Capt. F. W. Beechey on his celebrated voyage to the Arctic. He first noted the presence of coal beds at Cape Beaufort and speaks of "carbonized impressions of reeds, both fluted and plain, generally flat," which were taken by William Buckland,[1] who reported on the material, as indicating Carboniferous. As already noted, Collier found only Jurassic at Cape Beaufort.

Nearly 50 years passed before anything further was known from Cape Lisburne. From 1884 to about 1887 Henry D. Woolfe, while in the employ of the Pacific Steam Whaling Co., made annual visits to the region and sent to the United States National Museum a considerable collection of fossil plants. This material was studied by Lesquereux,[2] who enumerated the following forms:

Aspidium oerstedi Heer.
Asplenium dicksonianum Heer.
Asplenium foersteri Deb. and Ett.
Baiera palmata Heer.
Chondrites filiciformis n. sp.
Irites alaskana n. sp.
Pecopteris denticulata Heer.
Pinus? staratschini Heer.
Podozamites latipennis Heer.
Zamites alaskana n. sp.

Lesquereux concluded that the age of the beds was probably Neocomian.

In 1890 H. D. Dumars made a small collection of plants from the Corwin coal mine, which came ultimately to the United States National Museum. This collection, together with all of the Woolfe material, was elaborated by W. M. Fontaine for Lester F. Ward's monograph "Status of the Mesozoic floras of the United States."[3] Fontaine revised and changed many of Lesquereux's determinations and as a final result of his studies gave the following list of species:

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[1] Zoology of Captain Beechey's voyage, Geology, p. 173, London, 1839.

[2] U. S. Nat. Mus. Proc., vol. 10, p. 36, 1887; vol. 11, pp. 31-33, 1888.

[3] U. S. Geol. Survey Mon. 48, pp. 153-175, Pls. XXXIX-XLV, 1905.

Chondrites filiciformis Lesq.
Dicksonia saportana Heer.
Onychiopsis psilotoides (Stokes and Webb) Ward.
Cladophlebis vaccensis Ward.
Cladophlebis alata Font.
Cladophlebis huttoni (Dunk.) Font.
Podozamites distantinervis Font.
Podozamites grandifolius? Font.
Baiera gracilis (Bean) Bunb.
Ginkgodium? alaskense Font.
Ginkgo digitata (Brongn.) Heer.
Ginkgo huttoni (Sternb.) Heer.
Ginkgo huttoni magnifolia Font.
Nageiopsis longifolia Font.

Fontaine discussed this flora at some length, his final conclusion being stated as follows: "The age of the formation yielding the Alaskan fossils, as indicated by them, is not older than the Lower Oolite and not younger than the Lower Cretaceous but is probably between them." On the basis of this statement Ward called the Cape Lisburne plants "Jurasso-Cretaceous."

In the preliminary study of Collier's material I took occasion to go over some of the identifications made by Fontaine and felt obliged to dissent from several of them. For example, the specimen which Fontaine determined as *Podozamites distantinervis* Font., a well-known Potomac species, I called *P. lanceolatus latifolius*, a Jurassic form. It appeared that Fontaine's great familiarity with the Potomac flora had led him to give undue weight to certain resemblances between them, and, as it then seemed to me, he made identifications which entirely vitiated the age determination. My conclusion was stated as follows: "I can see no valid reason for regarding this flora as other than Jurassic, or in any event as other than identical with the flora from eastern Siberia, the Jurassic age of which is, so far as I know, universally accepted." I expressed a similar view in my paper "The Jurassic age of the 'Jurassic flora of Oregon'"[1] and still entertain it.

The following is the complete list of species as given by me in the preliminary report made to Collier,[2] with the corresponding identifications of the present paper in brackets:

Cladophlebis huttoni (Dunk.) Font. [=C. huttoni].
Dicksonia n. sp.? [=Coniopteris burejensis].
Dicksonia burejensis Zalessky [=Coniopteris burejensis].
Tæniopteris parvula Heer [=Pityophyllum nordenskiöldi].
Equisetum sp. [=E. collieri n. sp.].
Podozamites lanceolatus latifolius (Schenk) Heer [=P. l. eichwaldi].
Podozamites sp. [=P. lanceolatus].
Baiera palmata Heer [=Zamites megaphyllus].
Phœnicopsis angustifolia Heer [=P. angustifolia].
Phœnicopsis speciosa Heer [=P. speciosa].
Pagiophyllum kurrii (Pomel) Schimp. [=P. kurrii].
Stachyotaxus septentrionalis? (Ag.) Nath. [=P. kurrii].
Taxites subzamoides? Möller [=P. kurrii].
Ginkgo huttoni Font., n. var. [=G. digitata].

This revised list of species in the Collier collection is as follows:

Coniopteris hymenophylloides (Brongniart) Seward.
Coniopteris burejensis (Zalessky) Seward.
Cladophlebis huttoni (Dunker) Fontaine.
?Cladophlebis alata Fontaine.
Equisetum collieri n. sp.
Podozamites lanceolatus eichwaldi (Schimper) Heer.
Podozamites lanceolatus (Lindley and Hutton) Braun.
Otozamites giganteus Thomas.
Zamites megaphyllus (Phillips) Seward.
Phœnicopsis speciosa Heer.
Phœnicopsis angustifolia Heer.
Elatides curvifolia (Dunker) Nathorst.
Pagiophyllum kurrii (Pomel) Schimper.
Pagiophyllum steenstrupi Bartholin?
Pityophyllum nordenskiöldi (Heer) Seward.
Fieldenia nordenskiöldi Nathorst.
Ginkgo digitata (Brongniart) Heer.

AGE OF THE PLANT-BEARING BEDS.

The bearing of these plants on the age of the beds in which they are found may now be considered. As already stated, the first material from the Cape Lisburne region was studied by Lesquereux, who regarded it as probably of Neocomian age. This material, together with a small later collection, was studied by Fontaine, who was somewhat in doubt as to whether it was Jurassic or lowest Cretaceous, the final compromise being to call the beds Jurasso-Cretaceous. I have long regarded the material as of Jurassic age, and the critical study of the Collier collection appears to have proved this assignment beyond reasonable question.

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[1] Am. Jour. Sci., 4th ser., vol. 30, p. 50, 1910.

[2] U. S. Geol. Survey Bull. 278, p. 29, 1906.

Of the 17 species from the Cape Lisburne region noted in the present paper, the following also occur in Amurland, eastern Siberia: *Coniopteris burejensis*, *C. hymenophylloides*, *Podozamites lanceolatus*, *P. l. eichwaldi*, *Phœnicopsis speciosa*, *P. angustifolia*, *Ginkgo digitata*, and *Pityophyllum nordenskiöldi*. These Amurland beds were regarded by Heer as belonging to that portion of the Middle Jurassic (Brown Jura) known as the Bathonian, and so far as known to me, this assignment has not been disputed. Seward in his late paper says: "The flora as a whole agrees closely with richer collections from Middle Jurassic strata."

In 1876 Heer [1] described a large number of Jurassic plants from the Government of Irkutsk, eastern Siberia, and in 1911 Seward and Thomas [2] reported on a small collection from the Balagansk district, in the same province. After making allowance for the changes in nomenclature there appear to be in these Irkutsk collections the following species in common with those from Cape Lisburne: *Coniopteris burejensis?*, *Ginkgo digitata*, *Phœnicopsis speciosa*, *P. angustifolia*, *Podozamites lanceolatus*, *P. l. eichwaldi*, and *Elatides curvifolia*.

A large collection of plants, in the main very well preserved, from beds regarded as of Bathonian or lowest Callovian age, near Kamenka, district of Izium, Government of Kharkow, was described by Thomas [3] in 1911. The following species from Cape Lisburne are represented in this flora: *Coniopteris hymenophylloides*, *Cladophlebis huttoni*, *Ginkgo digitata*, *Elatides curvifolia*, *Otozamites giganteus*, and *Podozamites lanceolatus*.

A small collection embracing 14 species from the western border of Mongolia, in Chinese Dzungaria, was described by Seward [4] in 1911. The Mesozoic strata of this region, according to Obrutschew, who collected the plants, reach the enormous estimated thickness of 3,500 meters, thus approaching the thickness recorded by Collier for the Cape Lisburne region. The following species are common to the two localities: *Coniopteris hymenophylloides*, *Ginkgo digitata*, *Phœnicopsis angustifolia*, and *Podozamites lanceolatus*. On the basis of the plants the beds are correlated by Seward with the Middle Jurassic rocks of England and other parts of the world. Seward calls attention to the "remarkable resemblance between Rhætic and Jurassic floras as regards general facies," and adds: "It appears to be certain that some types persisted from the Rhætic period to the middle or even to the latest stage of the Jurassic era." This resemblance will be alluded to later.

Seward [5] has described a small flora from Caucasia and Turkestan, from beds of Middle Jurassic age or older, which includes the following species found also at Cape Lisburne: *Coniopteris hymenophylloides*, *Podozamites lanceolatus*, *Ginkgo digitata*, and *Phœnicopsis angustifolia*.

In 1876 Heer [6] described over 30 species of plants from the vicinity of Cape Boheman, Spitzbergen. The beds in which they were found were regarded by Heer as belonging to the Brown Jura (Bathonian), and Nathorst,[7] who revised the flora in 1897, then confirmed this position, but later [8] he procured evidence which induced him to regard the age as near or above the Oxfordian—that is, in the Upper or White Jura. The species from Cape Boheman represented in the rocks of Cape Lisburne are *Podozamites lanceolatus*, *P. l. eichwaldi*, *Ginkgo digitata*, *Phœnicopsis angustifolia*, and *Pityophyllum nordenskiöldi*.

In the paper last cited Nathorst also enumerates anew the Upper Jurassic plants from Advent Bay, Spitzbergen, *Fieldenia nordenskiöldi* and *Elatides curvifolia* being in common with Cape Lisburne. The flora of Franz Josef Land, regarded by Nathorst as younger than that of Cape Boheman and Siberia, appears to have nothing in common with that of the Alaskan locality.

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[1] Heer, Oswald, Flora fossilis arctica, vol. 4, pt. 2, pp. 28–86, 1876.

[2] Com. géol. Mém., new ser., pt. 73, 1911.

[3] Idem, pt. 71, 1911.

[4] Idem, pt. 75, 1911.

[5] Idem, pt. 38, 1907.

[6] Heer, Oswald, Flora fossilis arctica, vol. 4, pt. 1, pp. 26–47, 1877.

[7] Nathorst, A. G., Kongl. Svenska Vetenskaps-Akad. Handl., vol. 30, p. 6, 1897.

[8] Nathorst, A. G., Fossil plants from Franz Josef Land: Norwegian North Polar Exped., vol. 1, No. 3, 1900.

The large and interesting flora of the island of Bornholm, which was first described by Bartholin and later and more fully by Möller,[1] was regarded by the latter as of Rhætic or Liassic age. It is, as Seward has pointed out, "no doubt younger than the Rhætic floras of Scania, Tonkin, and Franconia, and the number of Lower Oolite species which it includes would seem to favor the view that its affinities are rather with Jurassic than with Rhætic floras of other regions." This statement is, at least to some extent, borne out by the following species from Cape Lisburne which are found also in Bornholm: *Podozamites lanceolatus*, *Ginkgo digitata*, *Phœnicopsis angustifolia*, and *Pagiophyllum kurrii*.

Turning now to the rich and well-exploited Jurassic floras of England, we find *Coniopteris hymenophylloides*, *Ginkgo digitata*, and *Zamites megaphyllus*, of the Great Oolite (Bathonian), in common with the Alaskan flora here discussed. Similar beds in Sutherland carry *Coniopteris hymenophylloides*, *Ginkgo digitata*, and *Elatides curvifolia*.

The rich Jurassic flora from Douglas County, Oreg., as worked up by Fontaine,[2] includes the following species which appear to be present also in the Cape Lisburne region, though not all are listed here under the same names: *Coniopteris hymenophylloides*, *Thyrsopteris murrayana*, *Cladophlebis vaccensis*, *Podozamites lanceolatus*, *P. l. latifolius*, *P. pulchellus*, *Ginkgo digitata*, and Phœnicopsis sp.

From the composition and wide distribution of this flora as outlined above, the final conclusion is reached that the Corwin formation of the Cape Lisburne region is undoubtedly Jurassic in age, belonging either in the upper part of the Middle Jurassic or Brown Jura, or the extreme lower portion of the Upper Jurassic or White Jura—that is to say, it is probably not older than the Bathonian and certainly not younger than the Oxfordian.

DISTRIBUTION OF JURASSIC FLORAS.

GEOGRAPHIC RANGE.

At this point it may be of general interest briefly to review the character and geographic range of Jurassic floras, especially as developed in Arctic and Antarctic regions. The wide areal distribution of Middle and Upper Jurassic floras has long been one of the marvels of plant distribution. The living flora, of course, affords many individual examples of wide distribution, such as those found throughout the Tropics of both hemispheres, and others, chiefly weeds, that have, largely through human agencies, spread widely over temperate lands, but altogether these plants form but an insignificant part of the whole flora, whereas in Jurassic time a large percentage of the whole flora was practically world-wide in its range.

In Alaska well north of the Arctic Circle is found the interesting flora described in this paper. Although only a few fossil species are at present known to occur at Cape Lisburne, it is more than probable that the number would be greatly increased by careful examination, but the region is difficult of access and we must possibly await the exploitation of its coal resources before adequate investigation of the flora will be made.

The Jurassic flora has been found at a number of other localities in Alaska, the farthest north being a point between Icy Cape and Wainwright Inlet, about 180 miles northeast of Cape Lisburne. Another locality is near Nikolai, in the Copper River region, which has afforded a single species of Sagenopteris that is closely related to a form from the Lower Oolite of Italy and has also been found in Oregon and California. This species came from a bed now known as the Kennicott formation,[3] where it was found in association with marine invertebrates of Upper Jurassic age. The largest representation of Jurassic plants in Alaska, aside from that of Cape Lisburne, is found on the north shore of Cook Inlet, where seven or eight species were obtained. These occur in the "Enochkin formation" of Stanton and Martin,[4] in intimate association with marine shells regarded by these authors as the equivalent of the Callovian of European standards, or the upper part of the Lower Oolite of English geologists. The last Alaskan locality to be mentioned is Herendeen Bay, which has yielded a single species of Pterophyllum.

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[1] Möller, Hjalmar, Kongl. Svenska Vetenskaps-Akad. Handl., vol. 36, No. 6, 1903.

[2] U. S. Geol. Survey Mon. 48, pp. 47–145, Pls. VI–XXXVIII, 1905.

[3] U. S. Geol. Survey Bull. 448, pp. 31–43, 1911.

[4] Geol. Soc. America Bull., vol. 16, pp. 397 et seq., 1905.

The only other important North American localities are those in Oregon and California, which together have afforded 101 forms. The collections from these localities are especially rich in forms of Cladophlebis, Tæniopteris, Sagenopteris, Nilsonia, Pterophyllum, Ctenis, Ctenophyllum, Podozamites, and Ginkgo. No less than 47 per cent of these species are found also in Jurassic beds in other parts of the world, notably in Alaska, eastern Siberia, and Yorkshire, England.

The areas geographically nearest to the Alaskan localities are those of eastern Siberia. In 1876 Heer published his first paper on the flora of these areas, which included material from Kajamundung, Ust-Bali, the upper Amur River, and Bureja. This was supplemented in later years by the study of further material from the original localities as well as from Lena Delta, etc. The total number of species finally aggregated about 100, and many of them have since been identified in widely scattered parts of the world, the greatest number being common to the beds in Oregon and California and in Yorkshire, England.

As a complete enumeration of the Jurassic floras of the world is impossible for lack of space in the present connection, the following list of localities may be given as a partial indication of their wide range:

- United States:
  - South Dakota.
  - Wyoming.
  - California.
  - Oregon.
- Alaska:
  - Cape Lisburne.
  - Near Wainwright Inlet.
  - Nikolai.
  - Cook Inlet.
  - Herendeen Bay.
- England: Yorkshire.
- Scotland: Sutherland.
- France: Mammers.
- Germany:
  - Franco-Swabian area.
  - Northeastern area.
- Austria-Hungary:
  - Steierdorf, Banat.
  - Crojic, Galicia.
  - Krakau.
- Italy.
- Switzerland.
- Portugal.
- Sweden.
- Spitzbergen:
  - Cape Boheman.
  - Advent Bay.
  - Green Harbor
- King Karls Land.
- Franz Josef Land.
- Greenland:
  - Cape Stewart.
  - East Coast.
- Siberia:
  - Amurland.
  - Irkutsk.
  - Lena Delta.
- Chosen (Korea).
- Japan.
- Caucasia.
- Turkestan.
- India:
  - Cutch.
  - Jabalpur.
- China:
  - Tyskyp-Tag.
  - Border Hami Desert.
- Australia.
- New Zealand.
- Graham Land: Hope Bay.

The flora of Graham Land, which has recently been carefully elaborated by Halle,[1] is worthy of more than passing notice. This flora comprises 61 forms dispersed among the larger groups as follows: Filicales 25, Cycadales 17, Coniferales 16, unknown 3. It is of interest to note that the Ginkgoales, which form an important and varied element in the northern hemisphere, are entirely absent from the Antarctic locality, as indeed they are from the Gondwanas of India, and that Podozamites, which is abundant and variable in the north, is absent from the Hope Bay collection and is represented only by doubtful fragments in the Indian localities. Of the 22 species from Graham Land that were previously known, 9 are common to the Lower

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[1] Halle, T. G., Mesozoic flora of Graham Land: Wissensch. Ergebnisse der schwedischen Südpolar-Expedition, 1901–1903, vol. 3, pt. 14, pp. 1–123, Pls. I–IX, 1913.

Oolite of Yorkshire, England, 8 to the Upper Gondwanas of India, and 5 to the Jurassic of California and Oregon. In the nearest continent, South America, there are no floras of any importance that can be considered contemporaneous with this Antarctic flora.

With the foregoing outline of the distribution of Jurassic floras in mind, we are perhaps in a position to draw certain tentative conclusions as to their probable avenues and means of dispersal and climatic requirements. The systematic groups with which we mainly have to deal are the Filicales, Equisetales, Cycadales, Ginkgoales, and Coniferales.

MEANS OF DISPERSAL.

The chief factors which are adduced to explain the distribution of living plants are animals, especially birds and mammals; water, especially streams and ocean currents; air currents; and, of course, human agencies.

In considering the distribution of Jurassic plants we may at once eliminate mammals, which were in Jurassic time on the threshold of their development, and birds, which were represented by a single known type (Archæopteryx) that at best must have enjoyed but limited powers of flight. There remain, therefore, only air and water transportation to account for the distribution of Jurassic plants. None of the plants is believed to have possessed any marked mechanism for wide and systematic dispersal.

The ferns of the Jurassic period are believed to have been homosporous, which implies the production of vast numbers of spores of relatively short-lived vitality. A considerable number of living ferns having spores of this character are widely distributed on both hemispheres. The male fern is an example; a single plant, according to Bower, may produce in one season 5,000,000 spores, which are particularly well adapted to wind dispersal. That ferns may pass over at least 25 miles of open water is shown by Treub, who found that on the island of Karakatau, which had been completely wrecked and sterilized by a volcanic outburst, within three years 12 species had already become reestablished. While the air currents may have been competent to accomplish this, the possibility of other agencies, such as transportation by birds, ocean currents, or man, should not be ignored.

The Equisetales were not an important element in the Jurassic flora, being mostly represented by fragmentary material referred to Equisetum or Equisetites. Although many of the living species enjoy a wide distribution, little evidence is available as to their means of dispersal.

The Cycadales are seed-bearing plants, the seeds being of small or medium size. In the living species the seeds sink in fresh water and presumably would do the same in salt water. The length of time they would retain their vitality in salt water is problematical, though probably it would be very short. Their transportation for any great distance by water is open to question.

The Ginkgoales are very distinctly a waning type; in fact, they have come almost to the vanishing point, for the single living species is not believed to exist in a purely wild state. The identification of the early forms now commonly referred to the Ginkgoales is founded mainly on the foliage organs, and their seeds are not certainly known, but since the discovery of true Ginkgo in late Triassic or early Jurassic beds, and in practically its present form, the seeds have not infrequently been found. These seeds, like those of the living species, are of large size. They have no special means for extended dispersal.

In the living Coniferales there are certain minor devices for limited seed dispersal, such as variously winged seeds, but nothing that is especially remarkable. The seeds of Jurassic Coniferales, so far as known, possessed no special devices for wider dissemination than that usually taking place on a land surface.

AVENUES OF DISPERSAL.

The data presented in the foregoing paragraphs regarding the means for dispersal would seem to indicate a practically continuous land connection between the several localities during Jurassic time. With the possible exception of the ferns, whose spores might have been transported by air currents over very considerable distances of open water, none of the types appear to have possessed any mechanism or device by which they could have spread so widely without a practically continuous land route. It is of course possible that masses of earth covered with living vegetation—floating islands, so called—may have been torn from the land by streams and carried intact for considerable distances into the sea, as similar "islands" are now transported by the Amazon and other rivers, but the distance over which such masses would be effective in colonization is relatively short.

The striking similarity between the Jurassic floras of northwestern North America and eastern Siberia shows that the land connection between these localities during Jurassic time must have been practically continuous. The known presence of Jurassic beds at Herendeen Bay on the Aleutian Islands is at least a partial confirmation of the presence of this land bridge. If we may assume that the land adjacent to what is now Bering Sea was the center—or at least an important center—of distribution for the Jurassic floras, then, with communication established between the two continents, the way was open for a wide range over the northern hemisphere.

The presence of a well-marked Jurassic flora in the Antarctic region goes far toward justifying the presumption of a former land connection to that region, for the present distance is so great as to preclude the reasonable probability that the flora could have reached there otherwise.

PROBABLE CLIMATIC CONDITIONS.

With the abundant data now available certain tentative conclusions may perhaps be drawn as to the climatic conditions which existed during the life of the Jurassic flora. There is no evidence that this flora was depauperate or pinched as the result of adverse climate. On the contrary, the presence of large and luxuriant ferns, many of them tree ferns, and cycads, and of very abundant and large-sized leaves of Ginkgo, etc., especially in localities far north of the Arctic Circle, affords every evidence that the conditions of growth were favorable From the wide distribution of genera and species it appears that the conditions were also relatively uniform. In other words, there must have been abundant or sufficient moisture and a temperature that would permit the growth of such plants. Knowledge of the probable moisture and temperature requirements of a flora now represented only by fossil remains must be gained by a study of the nearest related living flora. On this basis it seems safe to assume that the Jurassic flora indicates a moist, warm, possibly subtropical climate.

THE FLORA.

CONIOPTERIS BUREJENSIS (Zalessky) Seward.

Plate V, figure 1.

Coniopteris burejensis (Zalessky) Seward, Jurassic plants from Amurland: Com. géol. Mém., new ser., pt. 81, p. 22, Pl. I, figs. 1–5; Pl. III, figs. 18–21, 1912.

Dicksonia burejensis Zalessky, Notes paléophytologiques: Com. géol. Bull., vol. 22, p. 192, Pl. III, figs. 1–4; Pl. IV, figs. 1–5, 1904; Knowlton, in Collier, U. S. Geol. Survey Bull. 278, p. 29, 1906.

Dicksonia n. sp., Knowlton, in Collier, loc. cit.

Cladophlebis vaccensis Ward, Fontaine, in Ward, U. S. Geol. Survey Mon. 48, p. 157, Pl. XXXIX, figs. 7, 8, 1905.

In 1904 Zalessky described a fruiting fern from Amurland under the name *Dicksonia burejensis*, at the same time calling attention to its resemblance to *Dicksonia coriacea* Schenk,[1] from the Jurassic of China, *D. concinna* Heer, from Amurland, etc. In his recent work, cited above, Seward redescribed and refigured the Zalessky specimens, together with additional material recently procured, under the name *Coniopteris burejensis*, largely on the ground that the fossil is undoubtedly congeneric with *Coniopteris hymenophylloides*. If it is to be held that Coniopteris is congeneric with Dicksonia, then the former is untenable, for it dates from 1849, while Dicksonia was founded in 1788. However, as there is some doubt as to their generic identity it may be well enough to retain the form under Coniopteris. It has usually been assumed that these plants belong to the family Cyatheaceæ, but of this more will be said later.

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[1] Schenk, A., Jurassische Pflanzen, in Richthofen's China, vol. 4, p. 254, Pl. LI, fig. 2; Pl. LII, figs. 5, 6, 1883.

The salient features of *Coniopteris burejensis* are described by Seward as follows:

> Frond bipinnate or probably tripinnate; pinnæ linear-lanceolate, attached to a comparatively slender rachis along the margins of which the pinnæ axes and the lamina of the basal pinnule on the lower side of the pinna are decurrent. The pinnules may be oval and serrate, like those of *C. hymenophylloides*, or longer and narrower, the linear lamina being serrate, or more deeply dissected into small oval segments; the latter form appears to be identical with that of some of the specimens described by Heer as *Dicksonia gracilis* and *D. glehniana*. In the larger examples the rachis is broader; the more widely separated pinnæ give a more open habit to the leaf, in marked contrast to the more compact form. The venation is of the Sphenopteris type.

In spite of Seward's elaborate explanation of the diversity in form and appearance of the sterile fronds referred to *C. burejensis*, it is difficult to believe that all are correctly referable to a single species. The long, narrow pinnæ with linear serrate laminæ (cf. figs. 18 and 20 of Seward's Pl. III) may very well be the sterile portions of the form that bore the fruiting specimen, but it would seem that the longer, oval, slightly serrate pinnules such as are shown in his Plate III, figure 19, are too different to have come from the same species. However, the collection may have contained many specimens that were not figured and some of these may bridge the apparent differences.

The fine fruiting specimen from Cape Lisburne shown in Plate V of the present paper is referred with much certainty to *C. burejensis*. It is a frond of large size, being probably between 30 and 40 centimeters in length and at least 20 centimeters broad. It is tripinnatified, or quadripinnate. The main rachis, which is over 3 millimeters in diameter and slightly zigzag, was evidently very stiff and rigid. The primary pinnæ are remote, alternate, at irregular distances, and spreading at the tips, giving the frond a very open, spreading effect. The rachis is relatively strong and somewhat angled. The secondary pinnæ are also alternate, sessile, lanceolate in general outline, and cut into numerous linear, deeply cut pinnules. The sori are terminal on slightly reduced laminæ.

The single specimen referred by Fontaine[1] to *Cladophlebis vaccensis* Ward, a species first described from the Jurassic of Oregon, is at best very obscure. It does not have the nervation ascribed to *C. vaccensis*, though in the shape of the pinnules there is not much difference. It is undoubtedly the same as the form shown in Zalessky's Plate III, figures 1, 1a, and refigured by Seward in his Plate III, figure 19, and is to be referred to *Coniopteris burejensis*.

CONIOPTERIS HYMENOPHYLLOIDES (Brongniart) Seward.

Plate V, figure 2.

Coniopteris hymenophylloides (Brongniart) Seward, Jurassic flora of the Yorkshire coast, p. 98, Pl. XVI, figs. 4–6; Pl. XVII, figs. 3, 6–8; Pl. XX, figs. 1, 2; Pl. XXI, figs. 1–3, 3a, 4, 4a, 1900; Fontaine, in Ward, U. S. Geol. Survey Mon. 48, p. 59, Pl. VIII, figs. 1–3, 1905.

Sphenopteris hymenophylloides Brongniart, Prodrome, pp. 51, 198 [nomen], 1828; Histoire des végétaux fossiles, p. 189, Pl. LVI, figs. 4, 4b, 1829.

Adiantites amurensis Heer, Flora fossilis arctica, vol. 4, pt. 2, p. 94, Pl. XXI, figs. 6a, b; enlarged, figs. 6, c, d, 1876.

This is one of the most abundant and widely distributed of Jurassic plants, having been reported from the Antarctic, many localities throughout the Arctic, Siberia, China, Japan, Germany, France, England, and Oregon, and now from Alaska. As might be expected from the number of students who have handled it, it has been reported under several generic names (Sphenopteris, Thyrsopteris, Dicksonia, Adiantites, etc.), but it all seems conspecific and is best included under the somewhat noncommittal name Coniopteris.

This species is represented in the Cape Lisburne material by the single pinna figured, but fortunately this fragment is excellently preserved and there can be no doubt as to the correctness of its identification. It is, for instance, not to be distinguished from a specimen from the Jurassic of Yorkshire, England, figured by Seward.[2]

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[1] Fontaine, W. M., U. S. Geol. Survey Mon. 48, p. 157, Pl. XXXIX, figs. 7, 8, 1905.

[2] Seward, A. C., Jurassic flora of the Yorkshire coast, Pl. XVI, fig. 6, 1900.

The specimen from Douglas County, Oreg., figured by Fontaine,[1] has probably been correctly determined but is an indistinctly preserved fragment. The enlargements (figs. 2, 3) which purport to show the sori are, however, entirely incorrect, there being really no trace of the fruiting condition. The slightly involute margins of the tips of the pinnules were evidently mistaken by the artist for immature sori.

A comparison of the specimen from Cape Lisburne with *Adiantites amurensis* from Amurland as figured by Heer [2] shows them to be undoubtedly identical, and, as suggested by Seward,[3] there is no doubt about referring the Amurland specimen to *Coniopteris hymenophylloides*.

CLADOPHLEBIS HUTTONI (Dunker) Fontaine.

Plate VI, figure 3.

Cladophlebis huttoni (Dunker) Fontaine, in Ward, U. S. Geol. Survey Mon. 48, p. 161, Pls. XLI–XLIII, 1905; Knowlton, in Collier, U. S. Geol. Survey Bull. 278, p. 29, 1906.

This species—one of the most abundant ferns in the Cape Lisburne region—has been so fully described and illustrated by Fontaine in the publication above cited that it is unnecessary again to go over the ground. The one or two examples from the Collier collection are here figured simply for the purpose of showing that they are undoubtedly the same as the specimens identified by Fontaine as *Cladophlebis huttoni* (Dunker). From the general shape and disposition of the pinnæ and pinnules, as well as the character of the nervation, there can be no doubt, it would seem, as to the correctness of referring these fronds to the genus Cladophlebis, but whether they are to be positively identified with Dunker's *Neuropteris huttoni*,[4] from the Wealden of Hanover, is or may be quite a different thing. Fontaine is very positive on this point, saying: "This fern [*Neuropteris huttoni*] has an uncommon aspect, and it resembles so closely the ferns from Alaska that there can be no doubt that they belong to the same species," but of this I am not so sure. It appears that only one fragment of the Hanoverian plant was found, this being a portion of a very strong rachis about 5.5 centimeters long and two more or less perfect pinnæ. Dunker's figure was copied by Schimper,[5] who changed the name to *Alethopteris huttoni*, and the original specimen was later studied and again figured by Schenk.[6] Schenk's figure differs somewhat from the original one, showing apparently that the specimen is really somewhat less perfect than would appear from Dunker's figure. It seems not unlikely that this Hanoverian plant should be referred to *Cladophlebis denticulata* (Brongniart); at least it seems strikingly similar to some that have been so referred—such, for instance, as one figured by Seward [7] from the Jurassic of Yorkshire.

The figure of the type specimen of Dunker's plant shows the pinnæ to be, as in *Cladophlebis denticulata*, sessile but not decurrent on the main rachis, whereas in the Alaskan fronds the pinnæ are distinctly decurrent and, as Fontaine pointed out, there is an occasional pinnule on the main rachis between the insertions of the pinnæ. It was undoubtedly a very large fern. One specimen in the Dumars collection—shown in Plate XLI of Fontaine's report—is 32 centimeters in length, and as it lacks both base and apex was probably twice as long when perfect. The main rachis in this example was more than 5 millimeters thick. The secondary pinnæ have a tendency to be opposite on the rachis, though in the upper portion they may become somewhat alternate. They arise at an angle of about 45° and curve outward slightly so as to become approximately at right angles to the rachis. In the lower and middle portions of the frond the pinnæ are cut deeply into ovate-lanceolate, slightly falcate divisions or pinnules, these being mainly entire, though some of them are provided with a few low teeth; the pinnules are for the most part rather acute. The lower pinnules of the lower ultimate pinnæ are least united. Toward the ends of the ultimate pinnae and in the terminal portions of the compound ends they are more and more united and pass into lobes and teeth, the size being at the same time diminished.

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[1] Fontaine, W. M., U. S. Geol. Survey Mon. 48, Pl. VIII, fig. 1, 1905.

[2] Heer, Oswald, Flora fossilis arctica, vol. 4, pt. 2, Pl. XXI, figs. 6a–d, 1876.

[3] Seward, A. C., Com. géol. Mém., new ser., pt. 81, p. 19, 1912.

[4] Dunker, W. B. R. H., Monographie der norddeutschen Wealdenbildung, p. 9, Pl. VIII, fig. 1, 1846.

[5] Schimper, W. P., Traité de paléontologie végétale, vol. 1, p. 570, Atlas, Pl. XXXI, fig. 10, 1869.

[6] Schenk, A., Palæontographica, vol. 19, p. 217, Pl. XXIX [VIII], figs. 1, 1a, 1871.

[7] Seward, A. C., Jurassic flora of the Yorkshire coast, Pl. XIV, fig. 1, 1900.

The nervation is described by Fontaine as follows:

> The midnerve goes off very obliquely and at about two-thirds the distance to the end of the pinnule splits up into branches, after the fashion of Cladophlebis, so that the plant is a well-marked type of that genus and in the absence of fructification must be placed in it. The lateral nerves, in proportion to the size of the pinnules, are quite slender. They are immersed in the leaf substance and are not conspicuous. They go off very obliquely and are forked one or more times. The lowest are the most copiously branched. The forking is notably low down on the nerve, so that the branches are unusually long. On the lower side of the base of the pinnules one or more lateral nerves go off from the main rachis. In the more separated pinnules the lower lateral nerves curve away from the midnerve, but in the lobed and dentate forms the interior basal ones often curve inward toward it.

On taking everything into account it seems probable that this fern should receive a new name, but it is so robust and abundant a form that it probably had a wide distribution in Arctic lands, not being confined to the vicinity of Cape Lisburne, and rather than give it a name which might possibly prove to be a synonym of some form known from less complete material, I am permitting it to remain under the name given by Fontaine. It is very much to be doubted, however, that this fern is identical with the *Neuropteris huttoni* of Dunker.

?CLADOPHLEBIS ALATA Fontaine.

Plate V, figures 3, 4; Plate VI, figure 4.

?Cladophlebis alata Fontaine, in Ward, U. S. Geol. Survey Mon. 48, p. 158, Pl. XXXIX, figs. 9–11; Pl. XL, 1905.
Onychiopsis psilotoides (Stokes and Webb) Ward, idem, p. 155, Pl. XXXIX, figs. 3–6.
Pecopteris denticulata Heer, Lesquereux, U. S. Nat. Mus. Proc., vol. 11, p. 32, 1888.

It is with much hesitation that this species is permitted to remain under the designation given it by Fontaine in his review of the flora of Cape Lisburne, especially in view of the fact that Berry [1] has merged the original *C. alata* with *C. browniana* (Dunker) Seward, a common form in the Patuxent and Arundel formations of Maryland and Virginia. That it is identical with the Potomac forms is extremely doubtful, but that it is the same as the numerous specimens from Cape Lisburne that were so designated by Fontaine there can of course be no question. At first it was thought that this form represented the sterile foliage of *Coniopteris burejensis*, and this supposition may ultimately be verified. For instance, the portion of the sterile pinna shown in Plate V, figure 4, is certainly strikingly similar to the upper pinna on the right-hand side of the figure of *C. burejensis* shown in Plate V. They are of about the same size, have the linear pinnules set at the same strict angle, and are cut nearly to the same degree.

It is not to be denied that the sterile portions of the specimens here called *Cladophlebis alata* have a rather striking resemblance to *Onychiopsis psilotoides* (or *mantelli*, as it is more frequently called). Thus, the very large lower pinna shown in Plate V, figure 3, is similar in general appearance to the figure given by Seward [2] of a specimen of *O. mantelli* from the English Wealden. Both these specimens show well the strict habit of the plants, and both lack the finer details of the outlines of the ultimate divisions. In the Alaskan specimen the pinnules are somewhat larger, but otherwise the difference is apparently not great. It was, of course, this general resemblance which induced Fontaine [3] to identify certain specimens in the earlier collections as *Onychiopsis psilotoides*, yet it is impossible to distinguish these from a large number here referred to *Cladophlebis alata*. For instance, the pinna shown in Plate V, figure 3, is not to be separated from figure 5 of Fontaine's plate above cited.

On the whole it seems best, pending the finding of additional material, to leave this form under the name given it by Fontaine, with the frank confession that such disposition is recognized as neither adequate nor final.

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[1] Berry, E. W., Maryland Geol. Survey, Lower Cretaceous, p. 243, 1912.

[2] Seward, A. C., Fossil plants of the Wealden, pt. 1, Pl. II, fig. 1, 1894.

[3] Fontaine, W. M., U. S. Geol. Survey Mon. 48, p. 155, Pl. XXXIX, figs. 3–6, 1905.

EQUISETUM COLLIERI n. sp.

Plate V, figure 5.

Stem very little flattened or distorted, about 6 or 7 millimeters in diameter and about 5.5 centimeters long between the nodes, slightly swollen in the nodal region, and with about eight relatively very strong longitudinal ribs and corresponding channels; sheath very short, appressed; teeth apparently of the same number as the ridges, about 12 millimeters in length, slender and sharply acuminate at apex, each lying closely appressed in a groove; tubercles, or enlarged subterranean portions, present at the lower node.

This species is based on the only example noted in the Collier collections and has been named for the collector. As may be seen, it has been little flattened or otherwise distorted and may be viewed nearly in its entirety. It is chiefly remarkable for the very prominent ribs and corresponding channels, and the short sheath with the long, slender acuminate teeth closely appressed in the depressions.

I have very little doubt that this is the same as the form from Cape Boheman, Spitzbergen, described by Heer[1] under the name *Equisetum rugulosum*, though the present form is better preserved and admits of a fuller description of the essential characters. The size and the prominent ribs are evidently similar in both, though the Spitzbergen specimen is not swollen in the nodal region, and of course the character of the teeth can not be made out. Rather than make a doubtful identification, however, I have placed the Alaska specimen under a different name.

This species is also similar to the specimen of *Equisetum burejense* from Amurland shown in one of the figures given by Heer.[2] This figure shows a portion of a stem with parts of two nodes and an attached "tuber," as well as several scars, whence apparently other "tubers" have been broken. The figure of *E. collieri* shows the presence of a "tuber" of similar size and appearance, at least so far as can be made out, at the lower node. The size of the stem is similar in the two forms, though *E. burejense* is not swollen in the nodal region nor are the longitudinal ridges so prominent.

Seward,[3] in commenting on *Equisetum burejense*, says: "These incomplete specimens may be tubers of Equisetites, but they are hardly worthy of a specific name." This attitude of mind in dealing with obscure or biologically uncertain forms is not the right one, in my opinion, for if a plant is sufficiently well characterized to be used as a stratigraphic mark its usefulness is increased by giving it a definite name that can be employed for reference, whether it is biologically allocated or not.

Nathorst,[4] who reviewed Heer's Cape Boheman material, reduced not only his *Equisetum rugulosum* but also *E. bunburyanum* Heer and *Phytotheca lateralis*? Heer to Equisetites sp., remarking that they are too poorly preserved and doubtful to be maintained. The fine transverse lines on *Equisetum rugulosum* spoken of by Heer are, according to Nathorst, only checks in the carbonaceous covering. Be this as it may, there does not appear to be any doubt as to the correctness of referring the present Alaska form to Equisetum.

OTOZAMITES GIGANTEUS Thomas.

Plate VI, figure 2.

Otozamites giganteus Thomas, Jurassic flora of Kamenka: Com. géol. Mém., new ser., pt. 71, p. 84, Pl. VI, figs. 1, 2, 1911.

The single example figured is the only specimen of this species that has been found. It consists of a portion of the rachis about 4 centimeters in length and the basal portions of three leaflets, only one of which, however, is anywhere near perfect. This most perfect leaflet is 13 millimeters wide and is preserved for a length of about 4.5 centimeters and was presumably some 7 or 8 centimeters in length when living. The base is plainly heart-shaped, with the upper side slightly the longer and apparently a little overlapping the rachis; the point of attachment is approximately in the center of the leaflet. The margins of the leaflet are completely preserved only near the base, but so far as can be made out little narrowing is apparent. The nervation all arises at the point of attachment and thence radiates out with occasional forking to accommodate the enlarged area reached.

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[1] Heer, Oswald, Flora fossilis arctica, vol. 4, pt. 1, p. 32, Pl. VI, fig. 19, 1876.

[2] Idem, pt. 2, p. 99, Pl. XXII, fig. 8, 1876.

[3] Seward, A. C., Jurassic plants from Amurland; Com. géol. Mém., new ser., pt. 81, p. 20, 1912.

[4] Nathorst, A. G., Zur mesozoischen Flora Spitzbergens: Kongl. Svenska Vetenskaps-Akad. Handl., vol. 30, p. 12, 1897.

The type locality for *Otozamites giganteus* is Kamenka, in the district of Izium, in beds of Bathonian age (=upper part of Middle Jurassic or Brown Jura), and until the present record the species had not been found elsewhere.

ZAMITES MEGAPHYLLUS (Phillips) Seward.

Plate VII, figure 1.

Zamites megaphyllus (Phillips) Seward, Jurassic flora, pt. 2, Pl. X, figs. 4, 5; Pl. XII, figs. 1, 3–5, 1904.
Palæozamia megaphylla Phillips, Geology of Oxford, p. 169, Diag. XXX, fig. 6, 1871.
Irites alaskana Lesquereux, U. S. Nat. Mus. Proc., vol. 10, p. 36, 1887.
Baiera palmata Heer, Lesquereux, idem, vol. 11, p. 31, Pl. XVI, figs. 4, 5, 1888.
Nageiopsis longifolia Fontaine, in Ward, U. S. Geol. Survey Mon. 48, p. 171, Pl. XLV, figs. 1–5, 1905.
Podozamites grandifolius Fontaine?, idem, p. 167, Pl. XLIV, fig. 1.

Leaflets coriaceous in texture, long, narrow, strap-shaped, slightly falcate, abruptly rounded at base, narrowed from or below the middle to a long, slenderly acuminate apex; margin perfectly entire; attachment unknown but probably sessile by the narrowed base; nerves distinct, parallel, not forking unless at base (which has not been clearly seen), 20 or 25 in number, each separated by about 10 thin, very delicate intermediate veins.

This species is represented by nearly twenty examples, none of which is absolutely complete, as all lack the extreme base showing the point of attachment. The character of the extreme tip, however, is well shown in several specimens. The maximum length observed is about 18 centimeters and the width 2.5 to nearly 3 centimeters. At least two of the specimens show that the base is becoming rounded to the point of attachment, but unfortunately none is quite clear at this place. The character of the nerves, both the larger and the fine intermediate ones, is plainly discernible in most of the specimens; they are fully described above.

It was at first my intention to describe this as a new species of Zamites, but on further consideration I found it impossible to distinguish the form from *Zamites megaphyllus* (Phillips), as described and figured by Seward [1] from the Great Oolite (Bathonian) of Stonesfield, England. Although Seward states that the English material consists almost entirely of detached leaflets, he was enabled to give the following diagnosis:

> Frond pinnate, pinnæ attached to the rachis at a wide angle, reaching a length of more than 30 centimeters and a breadth of over 3 centimeters; linear in form, attached by a slightly contracted concave basal surface, which is somewhat thickened; the lamina tapers gradually to an elongated acuminate apex, frequently falcate near the tip. Veins numerous and parallel, converging slightly toward the base and apex of the pinnæ.

This diagnosis, it will be observed, agrees absolutely with that drawn from the Alaska specimens. In the largest example figured by Seward,[2] which was 4 centimeters wide, the "lamina is traversed by numerous parallel veins between which, as shown in the drawing, occur finer longitudinal lines." In this particular, therefore, the specimens from Cape Lisburne agree with the English species and apparently there can be no doubt as to their being correctly referred to it.

There has been much uncertainty as to the generic reference for these fine leaflets. The first examples of this form were obtained at the Corwin mine, in the Cape Lisburne region, about 1885, by Henry D. Woolfe. These were studied by Lesquereux, who named them *Irites alaskana* on account of their presumed resemblance to leaves of the living Iris. He described them as follows: "Leaves thickish, linear-lanceolate, tubulose at apex, narrowed to the base, falcate, equinerved; median nerve obsolete; the lateral broad, equal." He also adds that the "nerves are about 1 millimeter in width [apart], not very prominent, equal, not separated by intermediate veinlets, very distinct." I have examined these specimens, which are preserved in the United States National Museum, and find them indistinguishable from the Collier specimens, except in size. The specimens of "*Irites alaskana*," with additional examples collected at the same locality by H. D. Dumars in 1890, were studied by Fontaine and referred to *Nageiopsis longifolia* Fontaine, a very abundant form in the Patuxent formation of Virginia and Maryland. It has long been my opinion, and in this I am supported by E. W. Berry,[1] that these specimens from Cape Lisburne have absolutely nothing to do with Nageiopsis nor of course with Irites. They have been compared carefully with the type and typical material of *Nageiopsis longifolia* Fontaine, and they are not the same. It is believed that they are not even congeneric.[2]

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[1] Seward, A. C., Jurassic flora, pt. 2, p. 111, 1904.

[2] Idem, Pl. X, fig. 4.

I am also referring to *Zamites megaphyllus* the specimens that Lesquereux[3] referred to *Baiera palmata* Heer and that Fontaine later referred with question to *Podozamites grandifolius* Fontaine. Both these authors fell into the error of regarding these leaves bottom side up—that is, as may be seen on referring to Lesquereux's figure 4, the part figured as the base is in reality the apex. Fontaine,[4] in speaking of these specimens, expressed doubt as to their affinity but finally referred them to his *Podozamites grandifolius*, which is now placed under *Ctenopsis latifolia* (Fontaine) Berry,[5] a rather rare species of the Patuxent formation of Virginia. Although these leaflets are if anything even larger than the Collier specimens here figured, they do not differ otherwise, at least so far as can be made out from their somewhat fragmentary condition.

PHŒNICOPSIS SPECIOSA Heer.

Plate VIII, figures 2–4.

Phœnicopsis speciosa Heer, Flora fossilis arctica, vol. 4, pt. 2, p. 112, Pl. XIX, figs. 1, 2; Pl. XXX, figs. 1–6, 1876.

There are several examples in the Collier collections that clearly belong to *Phœnicopsis speciosa* as described and figured by Heer from Amurland. Three of these have been figured, the one shown in Plate VIII, figure 2, being the most perfect. Another (Pl. VIII, fig. 3) is a detached leaflet or segment 11 centimeters in length and nearly 1 centimeter in width, which is indistinguishable from the specimen shown in Heer's Plate XXX, figure 3. Apparently this very characteristic species has not previously been recorded from North America.

PHŒNICOPSIS ANGUSTIFOLIA Heer.

Phœnicopsis angustifolia Heer, Flora fossilis arctica, vol. 4, pt. 2, pp. 51, 113, Pl. I, fig. 1d; Pl. II, fig. 3b; 1876.

The Collier collection contains several fragments that appear certainly to belong to *Phœnicopsis angustifolia*. Whether this species is really distinct or is referable to *P. speciosa*, as Seward[6] suggests, must be left to the future to determine. The present specimens are to be identified with *P. angustifolia* but throw no light on the question of their identity with *P. speciosa*.

PODOZAMITES LANCEOLATUS (Lindley and Hutton) Fr. Braun.

Podozamites lanceolatus (Lindley and Hutton) Fr. Braun (non Emmons), Verzeichniss der in der Kreis-Naturalien-Sammlung zu Bayreuth befindlichen Petrefacten, p. 100, 1840; Heer, Flora fossilis arctica, vol. 4, pt. 1, p. 35, Pl. VII, figs. 1–7, 1876; idem, pt. 2, p. 106, Pl. XXIII, figs. 1c, 4a–c; Pl. XXVI, figs. 2–10; Pl. XXVII, figs. 1–8, 1876.

The typical form of this variable type is represented by only a few fragments of rather large leaves that are too poor to figure.

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[1] Maryland Geol. Survey, Lower Cretaceous, p. 385, 1911.

[2] Since the above was written Hamshaw Thomas has published a short paper (Some new and rare Jurassic plants from Yorkshire: Cambridge Philos. Soc. Proc., vol. 17, pp. 256–262, Pls. VI, VII, 1913) in which he has described a new type of ginkgodian leaf under the name Eretmophyllum. In discussing the relationship of this new form Thomas suggests the possibility that these specimens, referred by Fontaine to *Nageiopsis longifolia*, may really be referable to his Eretmophyllum. Continuing, he says: "Fontaine's figure 5 might possibly be an Eretmophyllum leaf figured upside down, and the shape of the other fragments, thin distant veins almost parallel but sometimes forking, presents some points of similarity." A comparison of the specimens studied by Fontaine, as well as the Collier specimens here figured, shows that this suggestion is not without weight. This may account for the fact that the leaves or leaflets are always isolated, and further they may have been improperly oriented. However, until further proof is forthcoming, it seems as well to leave them under Zamites.

[3] Lesquereux, Leo, U. S. Nat. Mus. Proc., vol. 11, Pl. XVI, figs. 4, 5, p. 31, 1888.

[4] Fontaine, W. M., U. S. Geol. Survey Mon. 48, p. 167, 1905.

[5] Berry, E. W., Maryland Geol. Survey, Lower Cretaceous, p. 349, 1911.

[6] Seward, A. C., Jurassic plants from Amurland; Com. géol. Mém., new ser., pt. 81, p. 21, 1912.

PODOZAMITES LANCEOLATUS EICHWALDI (Schimper) Heer.

Plate V, figure 6; Plate VI, figure 5, part.

Podozamites lanceolatus eichwaldi (Schimper) Heer, Flora fossilis arctica, vol. 4, pt. 2, p. 109, Pl. XXIII, fig. 4, Pl. XXVI, figs. 2, 3, 9; Pl. XXVII, figs. 1, 5c, 1876; Nathorst, Zur mesozoischen Flora Spitzbergens: Kongl. Svenska Vetenskaps-Akad. Handl., vol. 30, p. 13, Pl. I, fig. 5, 1897.
Podozamites eichwaldi Schimper, Traité de paléontologie végétale, vol. 2, p. 160, 1870; Heer, Flora fossilis arctica, vol. 4, pt. 1, p. 36, Pl. VI, fig. 22c; Pl. VII, fig. 7c; Pl. VIII, figs. 1–4, 1876.
Podozamites lanceolatus latifolius (Schenk) Heer, Knowlton, in Collier, U. S. Geol. Survey Bull. 278, p. 29, 1906.

This form is very abundant and excellently well preserved in the Collier collections, and Heer also speaks of it as being an abundant form in the sandstones at Cape Boheman, Spitzbergen. At first Heer described it with full specific rank, but later he inclined to regard it as merely a variety of the omnipresent *P. lanceolatus*, and this is the view taken by Nathorst, who restudied Heer's specimens together with much additional material. Nathorst states that three forms of *P. lanceolatus* are present at Cape Boheman—*P. lanceolatus genuinus*, *P. l. eichwaldi*, and *P. l. ovalis*. It is quite possible that a large series might show that these forms so intergrade as to make it unsatisfactory to attempt to draw any sharp lines between them, but in the present collection they appear very distinct. For stratigraphic purposes the variety *eichwaldi* is certainly well marked, a fact which is of interest in the present connection as tending to connect the Cape Lisburne region with other undoubted Jurassic localities.

ELATIDES CURVIFOLA (Dunker) Nathorst.

Plate VIII, figure 1.

Elatides curvifolia (Dunker) Nathorst, Zur mesozoischen Flora Spitzbergens: Kongl. Svenska Vetenskaps-Akad. Handl. vol. 30, p. 35, Pl. I, figs. 25–27; Pl. II, figs. 3–6; Pl. IV, figs. 1–18; Pl. VI, figs. 6–8, 1897.
Lycopodites curvifolius Dunker, Monographie der norddeutschen Wealdenbildung, p. 20, Pl. VII, fig. 9, 1846.

The single fragmentary example figured is all that was noted of this species.

PAGIOPHYLLUM KURRII (Pomel) Schimper.

Plate VI, figure 1.

Pagiophyllum kurrii (Pomel) Schimper, Traité de paléontologie végétale, vol. 2, p. 250, 1872; Möller, Bornholms fossila Flora, Gymnospermer: Kongl. Svenska Vetenskaps-Akad. Handl., vol. 36, p. 31, Pl. V, figs. 10–12, 1903.
Araucaria peregrina p. p., Kurr, Beiträge zur fossilen Flora der Juraformation Württembergs, p. 9, Pl. I, fig. 1, 1846.
Moreauia kuhrii Pomel, Matériaux pour servir à la flore fossile Jurassique de la France, p. 21, 1849.

This species, described originally from the Jurassic of Wurttemberg, was found by Möller at Bornholm in beds regarded as either Rhætic or Liassic. Whether Möller has been correct in determining the Bornholm plants as identical with *Pagiophyllum kurrii* need not be discussed at this time, but it is certain that the specimens so figured and named by him are not to be distinguished from the Cape Lisburne example here figured. For instance, Möller's Plate V, figure 12, shows a short branchlet with broad, rather obtuse leaves that is certainly the same as the specimen from Cape Lisburne.

On the same piece of matrix and lying very close to the branchlet from the Collier collection is the apical portion of another branchlet which may or may not represent a very immature cone. It is not well preserved and hence can not be made out with certainty. Just below the "cone" are two or three leaves of the same size and appearance as those on the adjacent branchlet; below these the leaves become crowded and apparently narrower and shorter. It is, on the whole, probable that this is merely a growing tip in which the leaves are not fully developed.

PAGIOPHYLLUM STEENSTRUPI Bartholin?

Pagiophyllum steenstrupi Bartholin, Nogle i den bornholmske Juraformation forekommende Planteforsteninger, p. 101, Pl. V, figs. 6–8; Pl. VI, figs. 1, 2, 4, 1894; Möller, Bornholms fossila Flora, Gymnospermer: Kongl. Svenska Vetenskaps-Akad. Handl., vol. 36, p. 33, Pl. VI, figs. 1–3, 1903.

The Cape Lisburne material contains two minute fragments that appear to be the same as the tips of branchlets such as are shown in Plate VI, figure 3, of Möller's paper, cited above, but they are so small and uncertain as to make their identification more or less questionable.

These specimens also suggest *Stachyotaxus septentrionalis* (Ag.) Nathorst, as figured by Möller,[1] but there is not enough preserved to identify them certainly with that species.

PITYOPHYLLUM NORDENSKIÖLDI (Heer) Seward.

Pityophyllum nordenskiöldi (Heer) Seward, Jurassic plants from Amurland: Com. géol. Mém., new ser., pt. 81, p. 30, Pl. II, fig. 17; Pl. III, fig. 22, 1912.

Pinus nordenskiöldi Heer, Flora fossilis arctica, vol. 4, pt. 1, p. 45, Pl. IX, figs. 1–6, 1876; idem, pt. 2, pp. 76, 117, Pl. IV, fig. 8c; Pl. XX, fig. 4, a, b; Pl. XXVII, fig. 9a; Pl. XXVIII, fig. 4, 1876.

This form is represented in the present material by several small fragments which are about 3 millimeters in width and 2 or 3 centimeters in length, evidently from the middle portion of the leaves. They have a single very strong median rib and show distinctly the peculiar transverse wrinkling so well known in leaves of this type. One fragment appears to show the presence of the longitudinal groove in the middle of the lamina that is regarded by Nathorst as so characteristic of this species, though the others in close proximity to it do not. It is probable, as Nathorst has suggested, that the transverse wrinkling is in the main a phenomenon of desiccation, though it was doubtless more or less connected with some structural peculiarity.

As Seward[2] has very well said, it is extremely difficult, if not impossible, satisfactorily to distinguish between many of the Rhætic and Jurassic leaves that have been described from time to time under the name Pityophyllum. Thus I can see no marked distinction between what is here called *P. nordenskiöldi* and *P. staratschini* (Heer) Nathorst,[3] from Advent Bay, Spitzbergen. It also agrees closely with *Taxites* cf. *gramineus* (Heer) as figured by Nathorst[4] from Franz Josef Land. Seward[5] has suggested that the leaves from the Jurassic of Oregon referred by Fontaine[6] to *Nilsonia parvula* (*Tæniopteris parvula* Heer) are to be regarded as belonging to Pityophyllum, but this can hardly be so, for they are much larger than any usually referred to Pityophyllum, and moreover they have a lateral nervation exactly as figured by Heer under *Tæniopteris parvula.*

FIELDENIA NORDENSKIÖLDI Nathorst.

Plate VII, figure 2.

Fieldenia nordenskiöldi Nathorst, Zur mesozoischen Flora Spitzbergens: Kongl. Svenska Vetenskaps-Akad. Handl., vol. 30, p. 56, Pl. III, figs. 16–27, 1897.

In the material from Cape Lisburne I find several more or less well preserved leaves that I am unable to distinguish from Nathorst's species, which comes from the Upper Jurassic of Advent Bay, Spitzbergen. The example figured is nearly perfect except that the nervation is rather indistinct, though careful scrutiny discloses the presence of about eight thin, parallel nerves. The point of the leaf is obtuse and rounded, the basal portion is narrowed to the point of attachment, and on the whole this leaf is absolutely indistinguishable from that shown in figure 17 of Nathorst's Plate III.

As Nathorst has pointed out, it is difficult, if not impossible, to distinguish between the present species and what Heer[7] has called *Podozamites ensiformis* and *P. cuspiformis* from the Irkutsk, eastern Siberia.

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[1] Op. cit., Pl. V, fig. 7.

[2] Seward, A. C., Jurassic plants from Amurland: Com. géol. Mém., new ser., pt. 81, p. 30, 1912.

[3] Nathorst, A. G., Zur mesozoischen Flora Spitzbergens: Kongl. Svenska Vetenskaps-Akad. Handl., vol. 30, p. 68, Pl. V, figs. 32–36, 1897.

[4] Nathorst, A. G., Fossil plants from Franz Josef Land: Norwegian North Polar Exped., vol. 1, No. 3, Pl. II, figs. 20–23, 1900.

[5] Seward, A. C., op. cit., p. 20.

[6] Fontaine, W. M., U. S. Geol. Survey Mon. 48, Pl. XVII, figs. 1–7, 1905.

[7] Heer, Oswald, Flora fossilis arctica, vol. 4, pt. 2, Pl. IV, figs. 8–10, 11, 12, 1876.

GINKGO DIGITATA (Brongniart) Heer.

Plate VI, figure 5, part; Plate VII, figures 3–5.

Ginkgo digitata (Brongniart) Heer, Flora fossilis arctica, vol. 4, pt. 1, p. 40, Pl. X, figs. 1, 5a, b, 6, 1876.
Ginkgo huttoni (Sternberg) Heer, Fontaine, in Ward, U. S. Geol. Survey Mon. 48, p. 170, 1905.
Ginkgo huttoni magnifolia? Fontaine, idem, p. 170, Pl. XLIV, figs. 7, 8.
Ginkgo multinervis Heer, Lesquereux, U. S. Nat. Mus. Proc., vol. 11, p. 31, Pl. XVI, fig. 6, 1888.

Leaves of Ginkgo are abundant in the Cape Lisburne collections, and it was undoubtedly a conspicuous element in this flora, as indeed it must have been in all the northern Jurassic and early Cretaceous floras. In the Oregon collections, for instance, the genus is represented literally by hundreds of specimens, and it was equally abundant throughout eastern Siberia.

This genus has been very much overburdened, for in dealing with such an abundance of specimens and multiplicity of forms one must needs make either many "species" to accommodate this diversity, or only one or two, and in view of the known variation exhibited by the single living species, the latter plan seems preferable. As a consequence, all the Alaska specimens are here considered as referable to the extremely variable *Ginkgo digitata.*

The first Ginkgo leaf known from Cape Lisburne—namely, that found in Woolfe's collection—was identified by Lesquereux as *G. multinervis* Heer, a species described from the Cenomanian beds of Atane, Greenland. The same specimen was later referred by Fontaine to *G. huttoni* (Sternberg) Heer, but while the segments are cut nearly to the base, it does not differ essentially from many referred to *G. digitata.*

The two rather fragmentary leaves from the Dumars collection Fontaine referred with a question to his *G. huttoni magnifolia*,[1] named from the Jurassic of Douglas County, Oreg. The validity of this variety will not be discussed at this time, and it is sufficient to say that the two specimens from Cape Lisburne are here referred to *G. digitata.*

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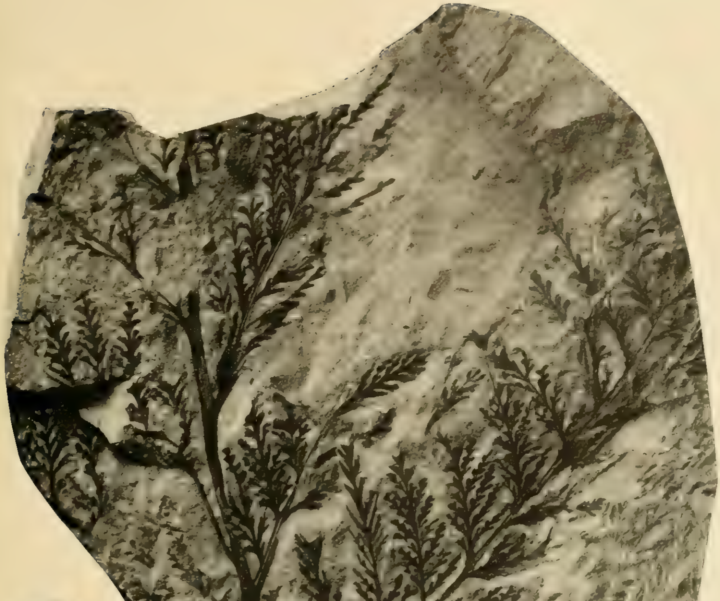
[1] Fontaine, W. M., U. S. Geol. Survey Mon. 48, p. 124, Pl. XXXI, figs. 4–8; Pl. XXXII, figs. 1, 2, 1905.

PLATE V.

PLATE V.

Figure 1. *Coniopteris burejensis* (Zalessky) Seward.
2. *Coniopteris hymenophylloides* (Brongniart) Seward.
3, 4. ? *Cladophlebis alata* Fontaine.
5. *Equisetum collieri* n. sp.
6. *Podozamites lanceolatus eichwaldi* (Heer) Seward.



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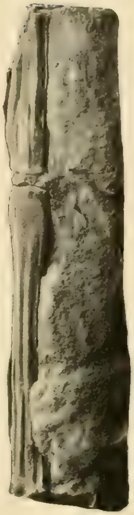

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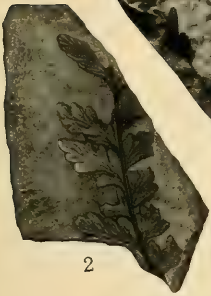

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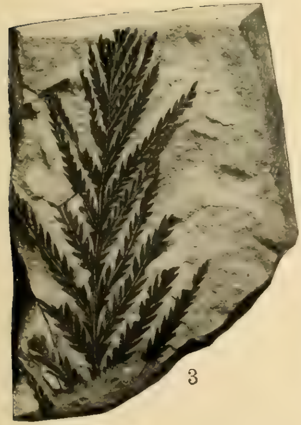

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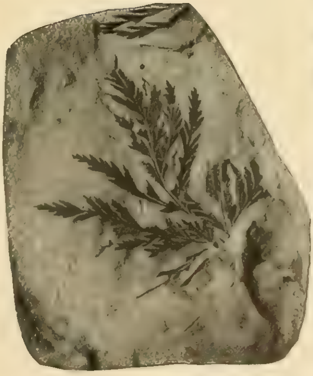

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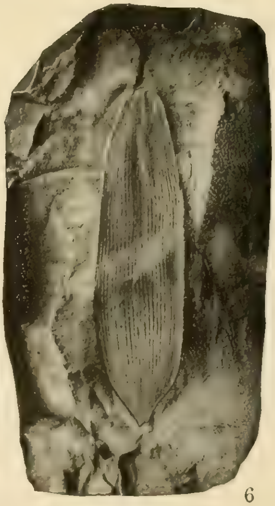

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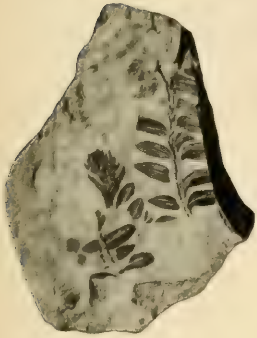
JURASSIC FLORA OF CAPE LISBURNE, ALASKA.

PLATE VI.

PLATE VI.

FIGURE 1. *Pagiophyllum kurrii* (Pomel) Schimper.
2. *Otozamites giganteus* Thomas.
3. *Cladophlebis huttoni* (Dunker) Fontaine.
4. ?*Cladophlebis alata* Fontaine.
5. *Ginkgo digitata* Heer and *Podozamites lanceolatus eichwaldi* (Heer) Seward.



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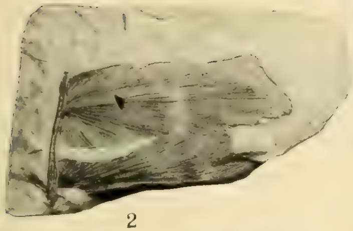

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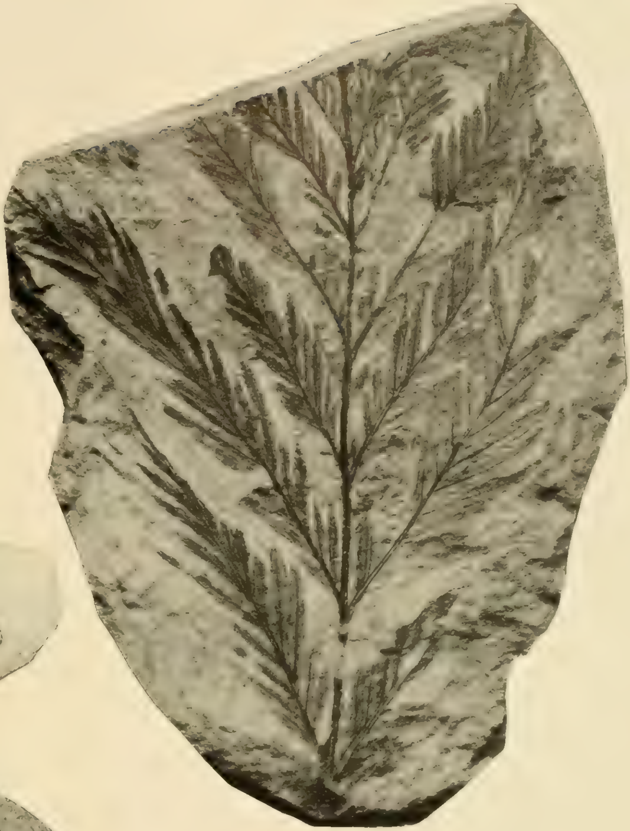

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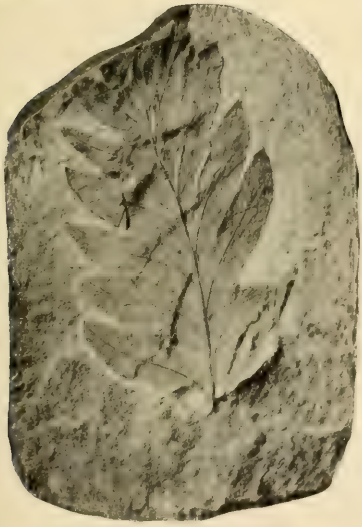

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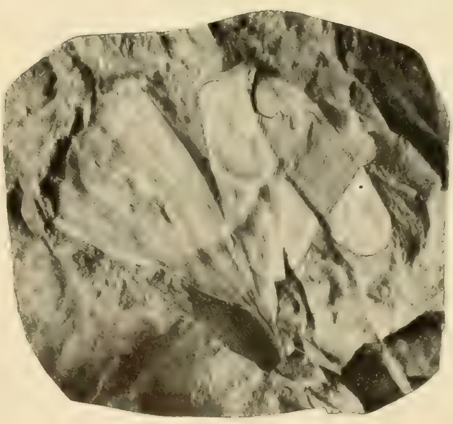

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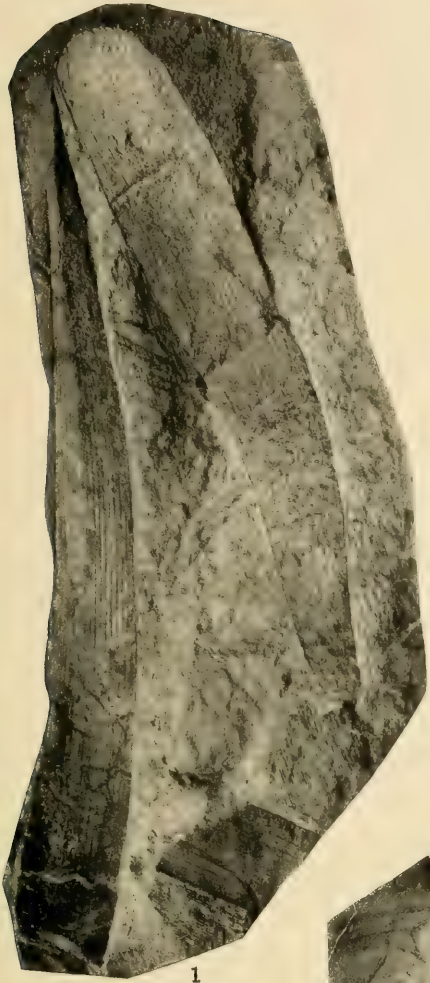
JURASSIC FLORA OF CAPE LISBURNE, ALASKA.

PLATE VII.

PLATE VII.

FIGURE 1. *Zamites megaphyllus* (Phillips) Seward.
2. *Fieldenia nordenskiöldi* Nathorst.
3–5. *Ginkgo digitata* Heer.



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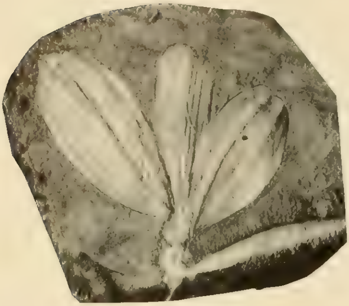

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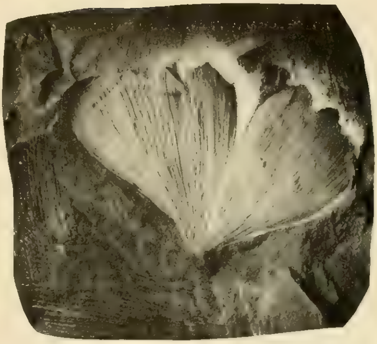

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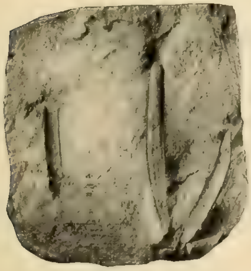

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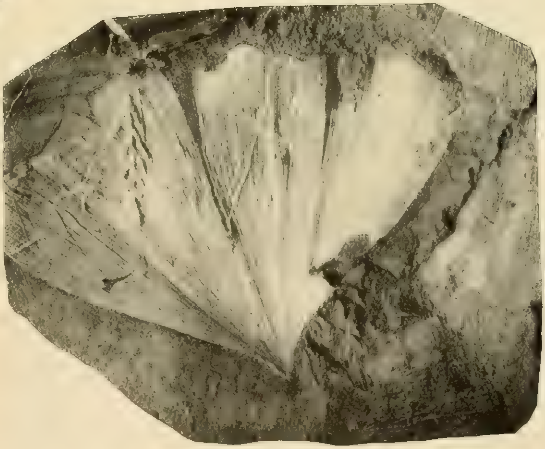

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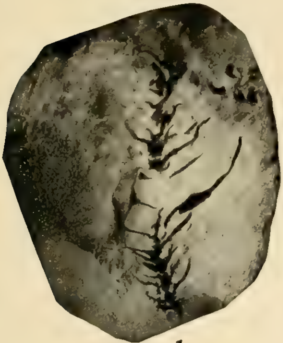
JURASSIC FLORA OF CAPE LISBURNE, ALASKA.

PLATE VIII.

PLATE VIII.

FIGURE 1. *Elatides curvifolia* (Dunker) Nathorst.
2–4. *Phœnicopsis speciosa* Heer.



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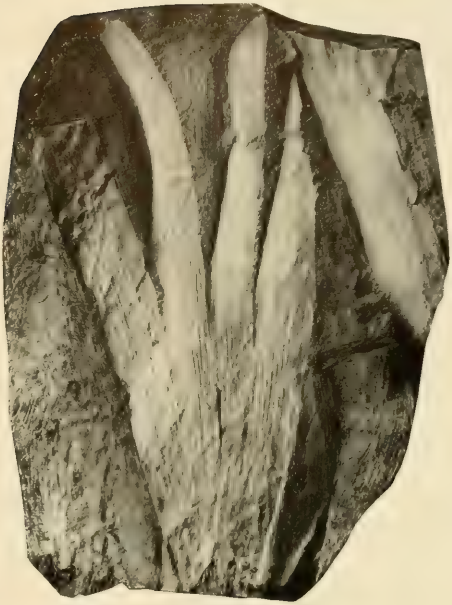

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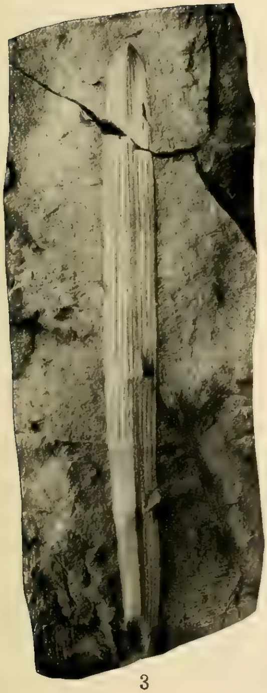

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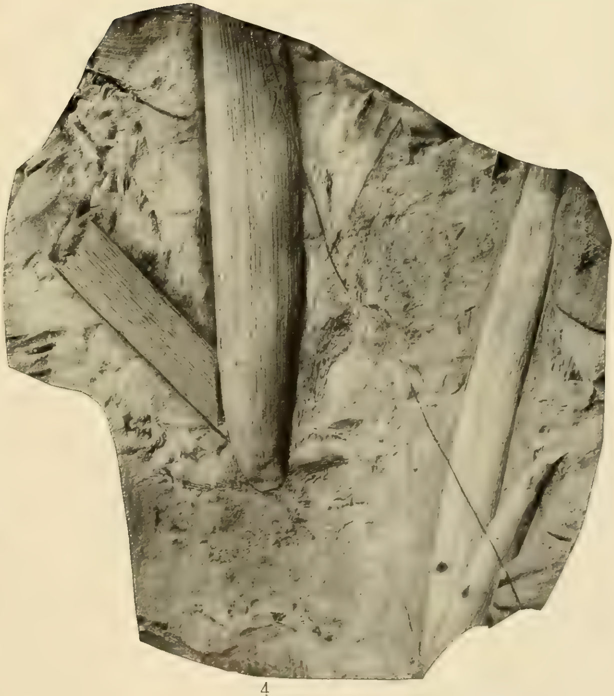

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JURASSIC FLORA OF CAPE LISBURNE, ALASKA.

RESINS IN PALEOZOIC PLANTS AND IN COALS OF HIGH RANK.

By David White.

INTRODUCTION.

The theory that coal is but peat, mainly of swamp types of formation, that has been transformed by normal geologic processes seems to have been completely demonstrated, though it is not fully accepted by many geologists and chemists. Examinations have shown that the coal substance is made up of plant débris, more or less decomposed and altered, mingled with and perhaps permeated by the now hardened but once liquid products of organic decomposition. Such being the case, we may conclude that all the parts and products of the plants were originally contributed to the peat formation and, either as fragmental remains or perhaps as chemical products of the decomposition of portions of the vegetal substance, may have entered into the composition of the peat. The evidence shows that varying proportions, in places nearly all, of the contributed plant materials were structurally obliterated before the peat-forming process terminated.

Naturally, in the process of building up peat those plant parts and products which were most resistant to the decomposing agents, principally bacteria and fungi, would survive longest and, other things being equal, would be most easily recognized in the undestroyed débris remaining in the coal. Among these decay-resisting products are the resins, waxes, spore covers, cuticles, seed coats, and bast of the plants of numerous kinds that are contributed to the peat.

Plants of types that produce resins and waxes are present in every region where peat is now in process of formation. Their fossil remains are present also in nearly every swamp that is found buried in the formations of later geologic ages, and in the low-rank coals found in these formations. Yet, because the presence of resins in the coals of higher rank has not been sufficiently demonstrated, it is believed by many, perhaps by most geologists and chemists, and even by some paleontologists, that resins never entered into the composition of these coals; that the higher-rank coals of all ages owe their very differences in rank to differences in the types of the plants from which they were formed, the absence of resin-producing plants being regarded as one of the conspicuous characteristics of the floras producing these coals; and that the great coal-forming floras of the Carboniferous period, to which the bituminous and higher-rank coals of most parts of the world belong, were destitute of resin-bearing plants. It is also urged by many foreign writers that the coals of high rank have not at any time existed as peats.

The fact that the presence both of the remains of resin-bearing plants and of resin itself in the high-rank coals of the Paleozoic and Mesozoic formations has not been generally recognized is due to the nature of the evidence rather than to the lack of it. The purpose of the present paper is (1) to show that resins have been contributed to the high-rank coals of the Cretaceous and Tertiary periods as well as to the coals of low rank which are characteristic of those periods; (2) to point out the evidence that the Carboniferous floras were possibly as richly productive of resins or resinous substances as the floras of later periods; and (3) to demonstrate, with illustrations of material both common and unique, the presence of abundant resinous material in Paleozoic coals. Observations as to the physical changes in the resins consequent on the alteration of the coals to successively higher ranks are given. Incidentally the paper sets forth further proof (which apparently is not superfluous) of the origin of high-rank coals as peats.

RESINS IN COALS OF LOW RANK.

The occurrence of fossil resins in the lignites of the Cretaceous period is known to all who have closely observed these fuels. They are present in almost all deposits of these lignites and are in some places so abundant as to constitute an appreciable portion of the coal. These resins have been derived, for the most part at least, from coniferous trees that have been contributed to the original peat from which the lignites or coals of higher rank were formed.

As ordinarily observed, without the aid of the microscope, the resins consist of very irregular lumps ranging from the smallest particles to fragments over an inch in diameter. Usually the larger pieces are more or less elongated and variously flattened or shapeless. Sometimes they are found in their original positions with reference to the remains of the trunks, branches, or organs which bore them as surface exudates or to cover wounds, but generally they appear to be scattered in a medium of more or less promiscuously mingled plant débris or vestiges, all cemented in a dark humic matrix ("carbohumin"), though in fact the débris is apt to be more or less distinctly stratified and assorted as to kind, size, and state of preservation in the strata of the coal bed. Thus the resins are much more abundant in some layers of the coal than in others, according to the kinds of ingredient plant material contributed to form these layers and the conditions attending their deposition in the peat swamp. The conditions of deposition controlled both the extent of decay of the variable plant débris and the disposition of the decomposition products, portions of which were usually carried in solution by water from the areas of peat formation.

The resins are generally yellowish, brownish, or amber-colored, translucent, and vitreously conchoidal in fracture, though some of the material is pale yellow and apparently granulose in texture. As is well known, the amber of the arts and most of the copal of commerce are merely fossil resins, the greater part of the trade supply of amber having been produced by several Tertiary species of pines now found fossil in the rocks bordering the Baltic Sea in eastern Prussia.

Substances regarded by certain authors as fossil resins have been described under many names, some of which follow:[1] Amber, ambrosine, ajkite, ambrite, berengelite, bucaramangite, brücknerellite, caproline, chemawinite, duxite, dinite, euosmite, fichtelite, gedanite, glessite, guayaquillite, hatchetine, hartite, kranzite, jaulingite, könlite, köflachite, leucopetrite, middletonite, muckite, neudorfite, piauzite, pyroretin, phylloretin, retinite, retinellite, refikite, rosthornite, rümanite, reussinite, scheererite, schleretinite, succinite, schraufite, sieburgite, simetite, walchowite, xyloretinite.

By far the greater part of these resins or doubtful supposed resins are from coals of Cretaceous and Tertiary ages or from peats.

Although at some localities and in certain layers of the lignites and subbituminous coals[2] small lumps of resin may be so numerous as to be conspicuous on the bedding planes or cross fractures of the coal, these are, after all, insignificant in quantity as compared with the resin in particles of microscopic size contained in the same layers or even in layers that reveal no resin at all to the unaided eye. These microscopic fragments are present in varying amounts in practically all the low-rank coals of Cretaceous or Tertiary age that have been microscopically examined. In some places they are so abundant as to impart a yellowish or brownish color to the layer. The relative amounts of these resins and resin compounds affect certain important qualities of the fuels, as will later be noted. The microscopic resins are numerous in kind and mode of occurrence, having been deposited in the cells and vessels of wood, bark, leaves, and seed coats and in the outer envelopes of spores and pollen grains. In the plant world of to-day they are produced by many different kinds of vegetation belonging to widely different classes of vascular plant life. A large percentage of the dry wood of certain conifers consists of resin. On the other hand, many types of plants, especially among the angiosperms, produce little or none.

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[1] See Leonhard, Gustav, Grundzüge der Mineralogie, 2d ed., pp. 381–383, 1860; also Dana, J. D., Mineralogy, 6th ed., pp. 996–1024, 1892.

[2] As defined by M. R. Campbell (Econ. Geology, vol. 3, p. 134, 1908), the subbituminous coals are distinguished from the bituminous by their mode of weathering, their less developed jointing and cleavage, and their higher moisture. On exposure to the atmosphere the lumps check irregularly, the resultant fragments, however small, being irregular in outline and having rough faces instead of cleavage planes. Weathering is characterized (very conspicuously in the longer-exposed fragments) by separation of the coal in plates parallel to the bedding, this process continuing to invisible limits They were formerly called "black lignites." The name lignite is now restricted by the United States Geological Survey to brown coals.

CONCENTRATION OF RESINS IN COALS.

The principle proposed by many of the older paleobotanists and emphatically reiterated by Renault and Bertrand, that the vestiges or remains of the plant structures contained in the coals represent, in general, those parts of the plant or those kinds of tissue which were most resistant to decay, is exceptionally well illustrated by the resins. It is well known that the delicate and soft structures of the plant, such as the parenchymatous and medullary tissues, are the first to disappear in the putrefactive processes necessary to the formation of peat, and that according to the duration of these processes, which is a variable factor, and to the agents, mainly bacterial, engaged, the decomposition becomes more and more complete, extending to the more resistant elements or tissues. Thus the decay of the less resistant starchy and cellulosic compounds is followed by that of the more resistant; the wood succumbs before the corky bark; the proteids disappear in advance of the waxes, and so on, until in the most "mature" and "amorphous" peats little is left except the most indestructible parts, such as the resin particles, fragments of cuticles that are composed of very resistant substances, and the resinous or waxy coverings of spores and pollen grains. Of these persistent portions of the plant the resins generally survive to the last the subaqueous biochemical or putrefactive processes concerned in the formation of peats.

From the foregoing statements it will be seen at once that the amount of resin in a coal, though varying of course according to the kinds of plants contributed to the formation of the mother peat, is largely determined by the extent to which the decay of the vegetal débris progressed. For, as the resin is the most resistant to decay, it obviously will, other things being equal, survive to form the largest percentages in those peats (coals) in which the decay of the plant débris has gone farthest. The successive decay of the less resistant enveloping and associated tissues gradually frees the resin particles, which, with the disappearance of the other plant materials, settle together in an accumulation, really a natural concentration. Hence a mature or "amorphous" peat formed by the far advanced decay of plants that have a comparatively low resin content may actually be much more resinous, as the result of such concentration, than another peat of the xyloid type, composed largely of wood which, though relatively rich in resin, has undergone comparatively slight decay.

What is said above as to the genesis of peats may be affirmed also of lignites, subbituminous coals, and coals of higher grades, all of which are but lithified and altered peats.

In most coals, especially the woody types, the percentage in volume of the resin still resting in the original cells or vessels in a piece of wood is further relatively increased by the mere loss of moisture and the other cell contents, and by the contraction and collapse of the cell walls under pressure, with the attending chemical changes. The great reduction in volume thus produced in the wood is accompanied, in the low-rank coals, by no observed shrinkage of the "rosin"-like resins. In the xyloid lignites—that is, lignites consisting largely of undestroyed or but partly decayed fragments of trunks, branches, or twigs—the amounts of resin may be very little if the woods represented were originally not very resinous; but in some coals highly resinous woods have been so reduced without obliteration of the cells that the volumetric percentage of resin therein has been more than doubled.

EFFECTS OF RESIN CONCENTRATION.

It has often happened during the formation of thick deposits of peat in a swamp that the water has in places been for a time too deep to be occupied by vascular plants growing in place. In these pools, sometimes small and irregular in form, where the water was temporarily open and the supply of oxygen was greater, the decomposition of the vegetal débris falling into the water could, if the water was not too stagnant, go so far as to leave only great quantities of resinous matter mingled with spore and pollen exines, wax residues, and cuticles. The same condition could exist also beneath the ordinary shallow-water cover in portions of the swamp if the oxygen supply was sufficient and the rate of accession of fresh plant débris was not too great. Layers of such matter may be recognized in many coals, though usually they are thin and obscured by underlying or superimposed, more or less coarse vestigial matter. They form the "fatty" parts of the bed. When the deeper water body was restricted, steady, and sufficiently stagnant to preclude both the inwash of considerable mineral sediments and the complete destruction of the organic vestiges, and the spore, pollen, wax, and resin concentrate was therefore low in ash and comparatively unstratified, the resultant "sapropelic" deposit is canneloid—that is, it forms canneloid layers or lenses—in the lignites, and these layers or beds, when the lignites were changed to coals of subbituminous and higher ranks, became cannel coals and oil rocks, though the latter, being generally formed in water bodies of greater extent and supposedly carrying innumerable algæ of low orders, and containing more mineral matter, are usually high in ash. The origin of the cannel type of coal is, in its essential features, the same without regard to the geologic age of its formation or the rank of the fuel, though the mutual proportions of the characteristic components, exines and resins,[1] may vary from place to place and from epoch to epoch. The concentrated resins and the resinous and waxy exines of the pollen and spores, variously mingled with microplankton vegetal elements, impart to the coals of the cannel and oil-rock group their high volatile, high heating, and high illuminating qualities and their tendency to fuse, even if they are of low rank, the resins and waxes being characteristically rich in hydrogen, the element of greatest calorific value, and relatively low in oxygen, the great heat neutralizer[2] in coals. The canneloid coal is high in volatile matter merely because its component plant remains or products are not only high in volatile but resistantly so.

The relative percentages of hydrogen and oxygen in the waxes and resins, as compared with the percentages of those elements in wood, peat, and lignite, are shown in the following table:[3]

Analyses of wood, resin, coals, etc.

	C.	H.	O.	N.	Available hydrogen.	H:O.
1. Wood	49.31	6.29	[a] 44.20	([a])	0.77+	0.14+
2. Peat	55.65	6.48	36.43	1.44	1.93	.18
3. Dopplerite	56.46	5.48	[a] 38.06	([a])	.73+	....
4. Lignite	74.86	5.32	18.51	1.31	3.01	.29
5. Fossil resin	78.61	9.52	11.77	....	8.05	.81
6. Wax	80.33	13.07	6.6	....	12.25	1.98
7. Bituminous coal	82.91	5.70	9.90	1.49	4.46	.58
8. Bituminous coal	87.52	5.26	7.22	....	4.36	.73
9. Semibituminous coal	91.62	4.85	2.32	1.21	4.56	2.09
10. Cannel	84.52	7.67	7.81	....	6.69	.98
11. Torbanite	84.56	10.99	[a] 4.45	....	10.43+	2.46+

[a] Nitrogen included with oxygen.

1. Petersen and Schädler, Liebig's Annalen, vol. 17, p. 179, 1836. Average of 24 woods.
2. Roth, Justus, Allgemeine und chemische Geologie, vol. 2, p. 642. Average of 10 analyses.
3. Kaufmann, F. G., K.-k. geol. Reichsanstalt Jahrb., vol. 15, p. 283, 1885.
4. Clarke, F. W., The data of geochemistry, 2d ed.: U. S. Geol. Survey Bull. 491, p. 714, 1911. Average of 10 analyses.
5. Gies, W. J., Science, vol. 25, 1897, p. 462. Resin, Amboy (Cretaceous) clays, Staten Island, New York.
6. Cornuba wax.
7. Clarke, F. W., op. cit., p. 718. Average of 40 analyses of coals from Ohio, Indiana, Illinois, Iowa, and Missouri.
8. Bureau of Mines Bull. 22, Upper Cretaceous coal, coking coal, Sopris, Colo. Fixed carbon (in "pure coal"), 62.3 per cent.
9. Idem, Pocahontas coal, Elkhorn, W. Va. Fixed carbon (in "pure coal"), 85.75 per cent.
10. Idem, Lesley, Johnson County, Ky. Cannel coal.

It will readily be seen that the presence of resins and spore and pollen exines must have its effect on all coals, the result being more conspicuous when the proportion of cannel-forming elements is greater. A high hydrogen-oxygen ratio ("pure coal" basis) in a coal below the semianthracite rank is to be regarded as indicating a more distinctly "bituminous" type of coal, for the bitumens are especially characterized by their very high hydrogen and their correspondingly low oxygen content. In the latter respect certain waxes approach the bitumens even more closely than do the resins, as is indicated by the wax analysis in the table. In this connection mention should be made of Hatchett's conclusions,[4] reached in 1804, that the resins and waxes were the sources of the bituminous quality in coals.

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[1] The term "resins" is here used in the broad sense, though in the descriptions of fossil specimens on later pages it signifies the characteristic "rosin"-like and amber-like resins.

[2] See White, David, The effect of oxygen in coal: U. S. Geol. Survey Bull. 382, 1909; Bureau of Mines Bull. 29, 1911.

[3] A larger series of ultimate analyses of coals of varying ranks may be found for comparison in the bulletins just cited and in Bureau of Mines Bull. 22.

[4] Hatchett, Charles, Roy. Soc. London Philos. Trans., 1804, p. 385; 1806, p. 109.

THE OBLITERATION OF THE RESINS.

It has been urged elsewhere[1] that it is important when discussing the origin of coal to recognize the operation of two great and fundamentally distinct processes or stages. The first process is the biochemical, which accomplishes the transformation of miscellaneous vegetal débris into peat. The second process, which follows or perhaps slightly overlaps the first, antedating the complete cessation of anaerobic bacterial action, is dynamo-chemical. Both processes are complex. Through the action of the dynamo-chemical agencies, apparently initiated and dominated in general by pressure but sometimes immediately controlled by contact-metamorphic heat, the peats have been transformed to lignites and coals of all higher ranks, being compressed, dehydrated, lithified, and partly devolatilized—that is, distilled. The progressive loss of volatile matter, which is still going on in most coals, is marked in particular by the elimination of oxygen in amounts relatively so much greater than the accompanying losses of carbon and hydrogen as to accomplish, in effect, a concentration of these two great fuel-producing elements that becomes more and more noticeable until the fuel approaches the anthracitic rank. The elimination of the oxygen permits a most important increase of the calorific value of the coal. The physical changes accompanying the dynamo-chemical process—that is, the effects of the pressure metamorphism—are found in the deformation of the plant remains, and the darkened color, reduction in volume, and increase of luster, jointing, friability, and even schistosity in the coal, as well as of cleavage and silicification in the surrounding strata.

The progress of the dynamo-chemical process is most conveniently gaged by the extent of the devolatilization (carbonization) of the fuel, as somewhat crudely determined by the conventional method of "approximate analysis" of the coal, the result being expressed in the ratios of the fixed carbon and volatile matter. Neither the initial organic chemical compounds nor those actually existing in any coal are fully known. The end product of the dynamo-chemical process is the approximate elimination of the volatile matter, the residue being graphite or, under conditions of intrusive contact, coke.

In the progressive transformation of peats, lignites, and subbituminous coals to fuels of higher rank, what becomes of the resins and waxes? For the answer to this question we are compelled, for the present, to depend largely on optical evidence.

The following observations relate, first, to the disappearance of the resins in the transformation of the Cretaceous and Tertiary coals. Later the question of the presence of resins in the coals of Paleozoic age will be considered.

Lump resins in widely varying amounts were found in all the lignites and subbituminous coals examined, though in many coals the pieces were very small. This is true of the xyloid lignites in the Fort Union Tertiary of North Dakota and Montana, the Cretaceous lignites of the Atlantic Coastal Plain, the Tertiary lignites of Arkansas and Texas, the subbituminous coals of the Cretaceous in the Denver Basin and in the Gallup district, New Mexico, the Eocene coals of the Cascade region of Washington, and the Cretaceous coals of the Hanna district of Wyoming. In all the coals of the lignitic and subbituminous ranks the resins have been found to retain the ordinary resin color, and apparently their other physical characteristics, although in some of the subbituminous coals the lumps show unmistakable effects of pressure, which has distorted them and here and there partly squeezed them into the joints of the bed. It is not probable, however, that the resins of these coals have remained wholly without chemical change from their original composition, notwithstanding their typically resinous appearance.

In the higher-rank coals—that is, in those grading through the lower bituminous ranks—the resins are found to have changed very greatly, having evidently undergone both physical and chemical alteration. This is shown in general, first, by the darkening of the color to a smoky brown; later, by the further blackening, crackling, and shrinkage of the lumps, which at a still later stage appear to be reduced to dark brownish-black spongy or granular residues, and still later, if the observations are correct, to a thin, fine, powdery black scale. The last state is difficult of recognition, and its correlation with the resin lumps is not without question. This change of the resins, which constitutes in effect a reduction (carbonization) of the substance, appears to have proceeded rapidly at a stage less than midway in the progress of the coals through the bituminous rank.

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[1] White, David, Econ. Geology, vol. 3, No. 4, p. 303, 1908; U. S. Geol. Survey Bull. 382, p. 62, 1909.

The behavior of the resins in the coals that are undergoing the somewhat advanced stages of dynamo-chemical alteration is suggestive of the action of recent resins when heated. In the highest ranks of the bituminous coals the resins are no longer recognizable as such to the unaided eye, and the identification of their residues in these fuels is at the present time wholly uncertain. They seem to have been practically obliterated, and the phenomena of their disappearance strongly suggest a mode of devolatilization under conditions favoring the retention of at least a part of their carbon in the coal. It is probably safe to infer that in the reduction of the resin, as well as in that of the other plant materials, the losses of oxygen are disproportionately large. The reduction of the resins appears to be coincident with a corresponding comparatively rapid deoxygenation of the coals themselves.

Without giving detailed observations regarding the fuels in the various coal fields, I will mention only a number of somewhat typical localities, where the successive stages in the alteration of resin may be well seen in the corresponding successive ranks of coal. It is understood that the "resins" here meant are the ordinary "rosin"-like or amber-like lumps. The rank of the coal will be, in a general way, shown by the accompanying percentage number, which indicates approximately the fixed carbon of the coal on the "pure coal" basis (ash, moisture, and sulphur free).[1] There is some variance in the degree of alteration in the resins at some mines and localities, just as there is variance (perhaps mutually corresponding) in the percentage of fixed carbon at the same points. These variations may be due to local differences in the stresses, to the advantageous position of the fuel at a certain point with reference to a fold, or even to the comparative resistance of the enveloping strata. The coals here discussed are all of Cretaceous or Tertiary age.

Among the subbituminous coals, in which the resins, though retaining their colors and general physical features, are more or less squeezed into the joints, especially in folded regions, mention may be made of the coals at Gallup, N. Mex.; Lafayette, Colo.; Renton and Centralia, Wash.; Red Lodge, Mont.; and the Sheridan and Hanna districts, Wyo.

In the low-rank bituminous coals the results of the dynamic influences are more evident, though there is but little visible evidence other than more advanced deformation and local discoloration. Thus the resins are generally more apt to be squeezed into the joints or along the bedding planes, in some places spreading out in large thin scales, although most of the lumps seem to retain their characteristic resinous aspect, in the low-rank bituminous coals of the Canon City field, Colo. (for example, Coal Creek, Radiant, or Fremont, averaging about 56 per cent fixed carbon); Shumway (55), Strong (56), Pictou and Walsenburg (58), in the Trinidad field, Colo.; Roslyn, Wash. (58); and New Castle (58), South Canyon (58), Black Diamond (59), and Sunlight (59), in the Glenwood Springs field, Colo. In some of these coals the lumps and scales of resin are in places turned more or less smoky brownish.

In the bituminous coals of slightly higher rank (fixed carbon averaging 60 per cent or a little higher) the resin lumps are not only deformed, being mostly flattened out as thin scales in the joints and bedding planes, but they have generally become of a dark sooty-brown color, most of them being more or less completely reduced to a brownish-black granular residue and some apparently to a mere black powdery film. The transitional stages from the smoky-brown or lighter-colored vitreous, conchoidal, semitransparent, and sometimes crackled lumps and scales to the reduced granular carbonaceous residues appear to be complete and abundantly illustrated. Examples of this later stage are found at Durango (Porter's), Colo. (61); the C. F. & I. mine at Crested Butte, Colo. (62); Carbonado, Wash. (62); Van Houten, N. Mex. (61); and Gulch, Colo. (63). In the coals of this rank (61 to 63 per cent fixed carbon in "pure coal") lumps retaining even in part the typical resin aspect are rarely to be found, though the very dark smoky-brown and largely reduced phases verging into the granular carbonaceous residues are seen at most of the localities mentioned.

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[1] These percentages, while probably fairly representative, are not to be regarded as showing with accuracy the average fixed carbon in the coal at the point mentioned. More exact estimates of the average percentages may be gained from the examination of the tables of analyses contained in Bulletin 22 of the Bureau of Mines.

In coals of a still higher rank the resins are apparently obliterated and no longer recognizable to the unaided eye. This is illustrated in the high-rank bituminous coals of Eocene age at Fairfax, Wash. (74); the Upper Cretaceous coal at Coal Basin, Colo. (76); the Eocene coal at Montezuma, Wash. (82); and the anthracites north of Crested Butte and at Floresta, Colo. In fact, I do not recall observing any material retaining megascopic resinous secretions in the high-rank bituminous coals (65 to 68 per cent fixed carbon) in the vicinity of Trinidad, Colo. (Sopris, Starkville, Cokedale, and Engleville), though carbonaceous traces, probably correctly identified as resin residues, are present. Fragments may, however, rarely be present here, especially in "bony" layers of the coal beds.

In certain of the coal fields where the alteration of the coals is regional the disappearance of the resin may be noticed in a restricted area, and even in a single very restricted coal group or possibly in a single bed, as, for example, in the Trinidad-Walsenburg-Raton field. In the Walsenburg district, at the northern end of this field, the low-rank bituminous coals of Upper Cretaceous age contain abundant resins, generally preserving their physical characteristics, though locally squeezed, but farther south along the same strata the resins are badly altered or apparently much reduced in the area of low-rank coking coal reached at Hastings and Berwind, about halfway to Trinidad, while still farther south, in the vicinity of Trinidad, the resins in the same coals are practically obliterated, the carbonaceous residues being seemingly lost in the finely jointed, granular high-grade coking coal. Other excellent areas for study are the Glenwood Springs coal field (also Upper Cretaceous) and the vicinity of Crested Butte, both in Colorado, where the regional differences in the fixed carbon are strongly marked. Another good region for observation is offered by the Tertiary coal areas of the Cascade field, in Washington.

My observations are less complete than is desirable and need confirmation. This may easily be accomplished by persistent and close field examination, which should take particularly into view also the precise stages of resin reduction corresponding to the respective stages of alteration in the coals themselves. However, the data now in hand appear to show that when the ordinary types (humic) of bituminous coals approach a rank roughly indicated by the development of 59 or 60 per cent of fixed carbon ("pure coal" basis), the megascopic resins contained therein reach a critical point, at which they begin rapidly to lose their resinous aspect and suffer reduction; and that before the coal has been carried by the dynamo-chemical process to 65 per cent fixed carbon the resin darkens, crackles, and shrivels, losing its characteristic features and apparently becoming reduced to a small coaly residue.

The period of marked alteration and reduction (carbonization) of the normal megascopic resins in the coals of Cretaceous and Tertiary age seems in general to coincide with that point in the devolatilization of the fuels which leads (other things being equal) to the development of the qualities essential to the production of high-standard commercial coke.

Whether the microscopic particles of resin still contained in the cells and canals of the plant or strewn about, freed by the decay of the surrounding tissues, on the ancient peat and mud layers have simultaneously undergone the same alteration and reduction as is observed in the readily visible lumps is yet to be determined by microscopical examination. It seems, however, fairly safe to assume that the internal resin secretions of the plants, which presumably are chemically identical with the wound resins, have similarly and contemporaneously suffered reduction and carbonization.

The typical coking quality, once developed, continues until the coal is carried approximately to the semianthracite rank, or, apparently, as long as sufficient volatile carbon and hydrogen remain in the fuel. Whether resins of any kind or any allied substances survive during this period remains to be determined. Their persistence, except as coalified residues, through the coals of semibituminous rank seems highly improbable. In this connection it will be remembered that the progressive deoxygenation of coals brought about by the dynamo-chemical processes results in the development in the higher bituminous ranks[1] of hydrogen-oxygen ratios (dry coal basis) similar to the ratios found in the resins. As already noted, the resins tend to impart a high hydrogen-oxygen ratio to the otherwise high-oxygen coals of the lower ranks, the highest ratios in these coals being found in the canneloid types. In the high-rank coals the high hydrogen-oxygen ratio necessary for successful and practicable coking is developed in the process of normal progressive devolatilization.

The period of coal alteration that is marked by the reduction of the resins appears to comprehend also a "deadening" of the cannel coals associated in the same groups of strata, as is to be expected. The apparent lack of cannel coals retaining their characteristic cannel qualities in the regions of semibituminous and higher-rank coals seems to be due to the reduction of the resins and other related canneloid elements. Beds or lenses, apparently deposited under cannel-forming conditions and probably once cannels, are present in the regions of semibituminous and anthracite coals, but though they retain a semblance to their original aspect and the massive conchoidal structure of cannels they have lost the special cannel qualities and are now often classed as "bone." I know of no occurrence of typical cannel coals or oil accumulations in formations and districts where the regional devolatilization of the coals has brought the humic coals to the rank characterized by 70 per cent of fixed carbon.

A question to be determined by chemical investigation is whether the reduction or carbonization (presumably a smothered devolatilization) of the resins has not aided in the deoxygenation of the remaining substance of the coal.

In areas like the Cascade coal field of Washington or the Glenwood Springs, Crested Butte, and Trinidad fields in Colorado, where in passing from one side of the field to another the coals are found to be progressively more and more altered through the dynamo-chemical process, there is no evidence whatever to serve as the basis for a belief that the plants growing in the district of low-rank coals differed essentially either in kinds or in resin content from those contributed to the original peat in the district of high-rank coals. The coals, some of which are practically continuous from area to area, are accompanied by similarly formed underclays, mostly containing roots in place, are similarly layered in benches apparently similarly composed, and are covered by shales or sandstones which, so far as observed, contain identical floras, thus showing approximate identity in the conditions of deposition of the fuel. It also must be remembered that the high-rank coals are similar in their mechanical constitution to those of low rank, containing fully as much woody matter, either in its jetlike condition of coalification or as "mineral charcoal," or, on the other hand, fully as much spore and vestigial material as the lower-rank coals in the same formation and basin. The progressive reduction (carbonization) of the cell walls, the dehydration of the remaining tissues, and the reduction of the resins or allied substances have naturally produced a decrease in the size of the wood fragments, but it is probable that the other material in the coal has suffered similar reduction, so that the proportions remain nearly the same. The progressively developed pressure cleavage, usually with more or less deformation, which on the whole becomes more and more evident in the more highly altered coals, not only tends to mask the texture of the woods, which are at the same time slightly reduced as the result of devolatilization, but tends in particular to crush and obliterate the mineral charcoal, which consequently contributes mainly to the dust and smut of the high-rank coal when it is mined and prepared for market. This is true also of the anthracites and other high-rank coals of the Paleozoic coal fields.

The observations as to the disappearance of the resins accord fully with the theory of the devolatilization (carbonization) of the coals as the result of thrust-pressure metamorphism, the coals being most altered, except in the vicinity of intrusives, where the pressure has been most intense and longest sustained, with variable but increasing strains.

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[1] U. S. Geol. Survey Bull. 382, pp. 53, 54, 1909.

RESINS IN PALEOZOIC PLANTS AND COALS.

The preceding discussion concerns mainly the coals of the Cretaceous and Tertiary periods, in which resin-bearing types of vegetation are known to have been abundant, as is shown by the fossil remains, and which, wherever they have not been too far altered by the dynamo-chemical process, are conclusively shown to contain resins of various kinds in microscopic deposits if not in plainly visible aggregations. We pass now to the consideration of the Paleozoic coals, in which the original occurrence as well as the present existence of resins has generally been doubted.

Most geologists and chemists seem inclined to the belief that the great differences which are almost universally supposed to exist between the Paleozoic coals (the so-called "stone coals"), on the one hand, and the Tertiary and Cretaceous coals (generally taken for granted to be lignites or brown coals), on the other, are due mainly to differences in the composition of the plants contributed to the formation of the coal in each great era. Prominent if not chief among these assumed differences is the supposed absence of resins in the coal-forming vegetation of the more ancient periods. The fact that in the apparent absence of resins visible to the unaided eye the Paleozoic coals strongly contrast with the characteristic low-rank coals of the later epochs, in which resins are so commonly obvious or are at least nearly always to be found if sought, has seemed strongly to support this theory. The persistent adherence to this conclusion is, however, remarkable in view of the well-known occurrences in the younger formations of whole areas and groups of high-rank coals. Neither the ultimate nor the proximate analyses of the high-rank bituminous Tertiary and Cretaceous coals afford any criteria for a chemical distinction between these coals and those of the same rank but of Paleozoic age. This circumstance harmonizes with the fact, well known to those having wide knowledge of coals of different ages, that at least very many specimens representing the higher ranks of Tertiary or Mesozoic coals are indistinguishable, to the unaided eye, from similar specimens of Paleozoic coals of the same rank, the identity of bedding, lamination, jetty layers, charcoal layers, and woody or minute débris being so complete that only by paleobotanic examination can the age of the sample be detected. The plant materials originally forming the high-rank Cretaceous and Tertiary coals were not less resinous than those entering the coals of lower rank in the same geologic group and province.

The criteria which serve as the basis for the belief, on purely paleobotanic grounds, that resins and waxes were present in the peat-forming vegetation of the Carboniferous period may be summarized as follows:

1. The dominant types of the Carboniferous vegetation, such as the lycopods, ferns, Calamariales, Cycadofilices, and Cordaitales, though mostly of lower orders than the dominant types of the Cretaceous and Tertiary coal fields, are hardly inferior to the latter in magnitude nor in their highly developed organization, as is shown by the anatomical structure of petrified material representing many of the forms. A great number of the lycopods, Cycadofilices, and Calamites were not only trees in size but were also provided with exogenous woody trunks and cortical developments equaling in complication of structure the plants of the present day. The inference is reasonable and justifiable that the terrestrial vascular plants growing under similar environmental conditions in the different geologic epochs have been subject to the same vital principles, have carried on the same functions, and have been composed of similar plant compounds, and that they have accordingly contributed plant products, including carbohydrates, proteins, fats, oils, waxes, and resins, similar, if not essentially the same, both in variety and in chemical composition, in all the epochs of great coal formation. Evidence is also found in the presence of secretory canals and cells in the nearest living relatives of the ancient plants, and in the occurrence in certain cannel coals of microscopic bodies which, though untested chemically, have an aspect so resin-like as to lead to their interpretation as probably resins.

2. The microscopic studies carried on by Renault, Williamson, Scott, Zeiller, Seward, C. E. Bertrand, and others, of petrified fragments of Carboniferous plants, some of which occur silicified or calcified in the midst of the beds of coal, have revealed the presence, in most of the

Carboniferous vascular plant types, of canals and cells that have been interpreted as secretory though few of them have been regarded with confidence as resin-containing and none seem to have offered criteria decisive as to this point. It is worth while in this place to cite some of the most important paleobotanic data bearing on the problem.

The Stigmaria roots which are so nearly omnipresent in the underclays of the Carboniferous coals and even in the layers of the coals themselves contain certain strands described [1] as "secretory." The Stigmaria are the roots of Sigillaria and Lepidodendron. It is therefore interesting to note the presence of secretory cells filled with dark-brown residues, associated with the transpiration tracts in the cortical tissues of Sigillaria [2] found silicified in the Permian at Autun, France. The structures are regarded by Renault as "gum cells with sheaths" and by Seward as "secretory strands." Seward [3] notes the occurrence in Lepidodendron of a secretory zone outside of the cylinder of secondary wood, embracing an "association of small cells, large spaces, and a certain amount of dark-colored material suggestive of tissue disorganization and secreted products." In the silicified material it is perhaps impossible to determine whether the residues noted in these fossil lycopods included resins.

Among the Paleozoic ferns numerous sacs supposed to have been of a "secretory nature" found in the inner zone of the cortex of the trunks of Zygopteris have been described by Scott,[4] and "gum canals" in Psaronius are pointed out by Zeiller.[5] The latter were the tree-fern trunks which bore the typical Pecopteris fronds so abundant and omnipresent in the higher coal measures.

In the Cycadofilices, which combine structures characteristic of the primitive gymnosperms, particularly the cycads, with others characteristic of ferns, especially the Marrattiaceæ, secretory structures have been observed in many types and are perhaps present throughout the group; thus Scott [6] notes that in Lyginodendron, the best-known type of the group, "sacs with dark contents, probably representing some kind of secretory organ, are frequent in all the soft tissues of the plant." The occurrence of secretory glands at the apices of the spines is characteristic of the fronds of this genus. In Ptychoxylon Renault [7] found in the outer cylinder of the cortex numerous elongated cells, many of them hypertrophied and filled with brown matter, "perhaps a gummy substance." The characters of the American material later to be described make it seem probable that these may be resin cells. "Numerous secretory canals much resembling the gum canals of recent cycads," and interpreted by both Renault [8] and Scott [9] as probably gum canals, are scattered throughout the thick cortical tissues of both the trunks and the petioles belonging to the genus Medullosa. To this genus probably pertain the petioles to be described later in this paper as containing a resinous substance. Secretory sacs or canals have been found also in the thick cortical tissues of Cycadoxylon and the Poroxylon type, and "gum canals" are reported as abundant and large in the hypodermal bands of Colpoxylon,[10] where they are sometimes filled with a brown substance thought to be possibly resin. Likewise Retinodendron, a type close to Cordaites, is said by Renault [11] to have abundant "resin tubes" and "secretory cells" in alternating zones of the cortex. The Cycadofilices embrace many of the commonest fernlike genera of the Carboniferous, including Neuropteris, Alethopteris, Odontopteris, Callipteris, Linopteris, and Mariopteris.

Especially interesting is the fact that Renault [12] observed in the branches of Arthropitus, a type supposed to be related to Calamites, many short longitudinal cells containing dark-colored bodies resembling resins, and many tubes interpreted by him as "gum reservoirs." The outer fleshy coats of the seeds of Cordaites are provided with canals which have been supposed to be intended for the storage of gum or tannin, and the parenchyma of the primary cortex of the trunks of the tree is said to envelop secretory sacs.

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[1] Seward, A. C., Fossil plants, vol. 2, pp. 158, 159, 1910.

[2] Renault, Bernard, Bassin houiller et permien d'Autun et d'Épinac, vol. 4, Flore fossile, pt. 2, pp. 222, 224, Pl. XLI, figs. 9 and 10, 1896.

[3] Op. cit., pp. 114, 145, 146, 168, fig. 183.

[4] Scott, D. H., Studies in fossil botany, 2d ed., vol. 1, p. 315, 1908.

[5] Zeiller, René, Bassin houiller et permien d'Autun et d'Épinac, vol. 1, Flore fossile, pt. 1, Pl. XXI, 1890.

[6] Op. cit., p. 368.

[7] Op. cit., p. 322.

[8] Idem, p. 295, Pl. LXX, figs. 1 and 2.

[9] Op. cit., pp. 434, 437.

[10] Renault, Bernard, op. cit., Pl. LXVIII, figs. 2 and 7; p. 203.

[11] Idem, Pl. LXXVII, figs. 10, 13, 14.

[12] Idem, Pl. XLVII, figs. 2, 3; Pl. XLVIII, fig. 2; Pl. LV, figs. 6, 7; Pl. LVI, figs. 6, 7; p. 91.

Mention should be made of the large canals and reservoirs and of unequal rounded granular bodies in the cortex of Hapaloxylon; of supposed gum cells near the nerve strands in Calamodendron and Dolerophyllum; and particularly of the occurrence of wood cells containing products regarded by Renault[1] as resinous, and of groups of cells full of "resin" in the large pith of the stems of Cedroxylon.

Finally it is important to note the occurrence, as described by both Renault[2] and Zeiller,[3] of numerous "gum tubes" filled with dark residues, associated with the sclerenchymatous hypodermal strands of the petioles known as Myelopteris and Myeloxylon. The suggestion that these canals are possibly resin-bearing appears to be fully justified, as will be pointed out in the description of carbonized remains from Montana, possibly belonging to the same genus. Before passing from the subject, it should be noted that the spore exines of the Paleozoic pteridophytes are generally believed, for good reasons, to have been protected by waxy, resinous, or gummy coverings like those of their living successors.

Many of the structures noted above are very likely mucilage or gum receptacles, but it is highly probable that some, at least, of the types were resin-secreting, and there is little doubt that they would have been so interpreted by paleobotanists had the occurrence of lump resins in the Carboniferous coals been fully recognized.

For many years I have observed in most of the Paleozoic coals of moderate or low bituminous rank the presence of great numbers of slender, rigid, glossy, cylindrical, needle-like rods of varying sizes, longitudinally embedded in very many of the fragments of mineral charcoal ("mother of coal"). Such carbonized fragments of wood are especially abundant in the Carboniferous coals of the interior basins, in places forming layers of considerable thickness. The slender rods, varying in diameter apparently according to the kind of tree, protrude from the macerated edges of the wood like the ends of broken needles. When examined closely they are found to be discontinuous. (See Pl. XI, fig. 4.) Even when the surrounding tracheids or wood cells did not completely decay away during the process of peat formation so as to expose them or leave them isolated, the collapse and reduction of the wood when partly macerated and under pressure was so complete and the wasted cell walls are so closely flattened that the slender parallel rods produce ridges where they lie near the surface of the "charcoal" fragments, which are usually reduced to a thin scale.

A typical example of a fragment of a compressed stem preserved as "mineral charcoal," from coal "No. 2," near Gerlaw, in western Illinois, is shown in figure 1, Plate IX. This fragment, which is split along the bedding plane, is but a portion of large piece of carbonized wood over 2 feet in length and several inches in width, lying in the midst of a well-laminated coal. Under the lens the very slender needle-like or rodlike casts are seen lying on or partly freed in the longitudinal grain of the wood. Many of the casts come very obliquely to the surface, and some are exposed for long distances. Others appear only as ridges in the "charcoal" scale to which the surrounding collapsed, softened, and wasted woody tissues were reduced. Numerous broken fragments of isolated casts lie strewn among vestiges of cuticles and other comminuted vegetal débris on the right, as may clearly be seen under the lens. A clearer presentation of the needle-like rods contained in this fragment of flattened carbonized wood is given in the four times enlarged figure of a portion of the same specimen (Pl. XI, fig. 4). In the inspection of this and the other figured examples of a common type of mineral charcoal the following points should be noted: (1) The needle-like rods lie in their original position in and parallel to the grain (tracheids) of the log; (2) they were hard and terete before the partial maceration of the surrounding wood cells, or, conversely, the tracheids collapsed and rotted away, while the rods were hard and resistant to pressure; (3) they were resistant to the biochemical agencies of decay, which liberated great numbers of them to be washed or strewn about on the mud or peat surfaces; and (4) they appear to have largely retained their form and their rigid though fragile character, while the peat has been altered by the dynamo-chemical process to coal of bituminous rank. These features leave no room for doubt that the rods are in fact but the casts or fillings of canals longitudinally traversing the tissues of the woods and petioles of some of the coal-forming plants. Their rigidity when existing in the fresh vegetation points to their nature as hard, brittle resins, gums, or waxes, but their resistance to the agents of decay and to the dynamic action argues against the interpretation of them as gums, while their mode of occurrence in internal canals points most strongly to their being resins instead of waxes.

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[1] Op. cit., p. 368.

[2] Renault, Bernard, Acad. sci. Paris Mém. sav. étrang., vol. 22, No. 10, p. 17, Pl. V, fig. 40, 1875.

[3] Op. cit., p. 284, Pl. XXVII.

The aspect and mode of occurrence of the fragments of carbonized wood ("mineral charcoal") so common on the bedding planes of coal is well shown in the piece of bituminous coal from the midst of the bed mined near Exeter, Ill., illustrated in figure 2, Plate IX. In this fragment, a part of which is shown enlarged four diameters in Plate X, the vessel casts, though of a type more slender than in the other specimen, are distinct. In some of the "charcoal"[1] fragments, like that in the upper left corner of the photograph, which nearly cover the bedding plane of the specimen, the fracture is closely parallel to the grain; but several of the other pieces are either macerated or abraded obliquely to the grain, so that the vessel casts protrude from the worn ends. It will be noticed further that many segments of the casts, completely released by decay of the wood, lie scattered here and there like fragments of broken needles. Some of them are but slightly moved from their original attitude as they were left by the decay of the surrounding tissues. Most of the large wood fragments on this piece of coal contain the needle-like vessel casts, though vestiges of wood in which none are seen are also present here, as in very many specimens and in most coals. It is probable that in the older peat swamps, just as in those of to-day, the resinous woods were more resistant to decay than the other types and therefore more likely to escape decomposition.

Many specimens are found in which the decay of the wood has been practically complete, so as to free the casts entirely. A good example of such isolated and broken casts is shown in figure 3, Plate IX, and four times enlarged in Plate XII. In this fragment, from a thin bony layer in the coal at Colchester, Ill., the rods are mingled with comparatively small numbers of large megaspore exines, minute fragments of cuticles, and scattered remains of the resinous or waxy, very resistant envelopes of certain seeds, particularly Cardiocarpon, two of which are present on the fragment illustrated. The casts, which vary in diameter and probably belong to several species of plants, at first glance suggest sponge spicules, but their ready combustibility betrays their vegetal origin. The specimen illustrated, which is about a quarter of an inch in thickness, is somewhat minutely laminated, some of the laminæ containing extremely thin layers of nearly amorphous carbonaceous silt. Between some of these laminæ are thin lenses and streaks of jetlike wood, all very much flattened. The layer here represented contains, as already explained (p. 68), much cannel-forming material, though the lamination with fine mineral sediment and stems gives it a "bony" character.

Carbonized wood fragments containing terete, brittle, decay-resistant vessel fillings, such as those shown in the accompanying plates, are abundant in most Paleozoic coals, at least in the interior basins of the United States, except where they are too far altered by dynamo-chemical agencies. A slight curvation sometimes noted possibly indicates a degree of elasticity or toughness in the original substance, but a degree of fragility in these fillings is shown by the ready fracture of the casts isolated by the decay of the rest of the tissues in the waters of the peat-forming swamp. That the contents of the canals were hard and round when the fresh wood fell to the surface of the swamp is shown by the maintenance of their tereteness while the surrounding tissues were undergoing maceration and deformation in the peat. Their free combustion, apparently with high volatile matter, plainly shows that they were not produced by occupation of the vessels by fine silts or other inorganic mineral matter. Their hardness and moderate rigidity at the time the woods decayed show, on the other hand, that they can not be merely hardened organic solutions occupying the canals after the woods became immersed in the swamp; otherwise they would have suffered deformation or perhaps would have again entered solution when freed from the rotting tissue. The waste of the cell walls on account of chemical reduction and the collapse of the partly macerated cells under pressure to a thickness of one-fifth to one-fifteenth, or possibly less, of their original diameter bring the rods into prominence, even where they are not actually exposed at the surface of the carbonized wood, now generally reduced to a thin scale. In this way the cast material is effectually concentrated.

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[1] In another place (Bureau of Mines Bull. 38, 1913) I urge that these "mineral charcoal" fragments are not cinders nor fragments, charred by burning at the surface of the swamp.

A close examination of the casts under low magnification shows that they resemble very dark brown or slightly orange-brown vulcanized rubber, the fracture being conchoidal and somewhat vitreous. Under stronger magnification the casts are found to be composed of an orange-russet or more or less yellowish semitranslucent substance. Cross sections, rounded or oval in form, of amber-like substance, similar to and probably identical with those composing the casts, are to be observed in thinly ground sections of coals from the same group, prepared and described by Thiessen,[1] and are regarded by him as probably transverse or oblique sections of resin vessel casts.

The cannel coals from the basal coal measures of Missouri and from the upper Pottsville in eastern Kentucky, examined by Thiessen, contain, in addition to the usual varied spore exines, numerous small irregular lumps of highly refractive substances slightly varying in their orange or yellow tones, which are interpreted by him, rightly, I believe, as resins. It will also be noted that in a recent important paper on the explosive elements in coals James Lomax[2] has described the occurrence of several microscopic bodies which, on account of their form and aspect, he regards as resins.

As in the Cretaceous and Tertiary coals the resins have persisted in form recognizable as resins until the coals have advanced some distance into the bituminous rank, it follows that remains of resins, if they were ever present and if they were similarly resistant to the biochemical agencies of coal formation, should similarly be found in Paleozoic bituminous coals of the same rank.

Accordingly they should be present in such Paleozoic coals as those of western Illinois, Iowa, and western Missouri. In 1908, immediately after an examination of the coals in several of the western coal fields, I was engaged in the eastern interior coal fields, where the comparatively low rank of the Paleozoic coals seemed favorable for resin survival. As a result of a close inspection, resin in small lumps was found in the coal at several of the comparatively few mines visited.

Lump resin was found in a dense, hard, bony layer in which very little woody matter was visible and the canneloid concentrates were mingled with a large percentage of mineral sediments at the Rutledge mine, a few miles northwest of Ottumwa, Iowa. At the La Salle shaft, in the eastern edge of La Salle, on the northern border of the Illinois coal field, the coal derived from bed "No. 2" (the bed from which the wood shown in fig. 1, Pl. IX, was taken) reveals a few small fragments of resin. One of these is shown, five times enlarged, in Plate XI, figure 1. The same block, about 5 inches in cube, of typical laminated bituminous coal, shows at different levels two other fragments of resin, one of which, exposed on the "butt" of the coal, is seen similarly enlarged in figure 3 of the same plate.

During a casual examination of the coal of upper Pottsville age at a small mine in one of the lower block coals near Brazil, Ind., the small but somewhat conspicuous fragment of resin shown five times enlarged in figure 2, Plate XI, was observed. It will be noted that the resin in this specimen, which comes from the midst of the bed, has been squeezed along both the bedding and the joint planes, so that its cross section has a "step" structure. A vertical joint just to the left of the resin lump is indicated in the illustration by the filling of narrow "white scale," whose irregular line in the photograph is due to the uneven fracture of the coal and the obliquity of the view. The opening of the joint and the deposition of the salts are probably of late date, while the deformation of the resin, which is squeezed along the bedding and vertical joint planes, probably dates from the post-Paleozoic uplift. The deformation of the resin is exactly comparable to that so familiar in the high-rank subbituminous and lower-rank bituminous coals of Cretaceous age in the western United States.

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[1] White, David, and Thiessen, Reinhardt, The origin of coal: Bureau of Mines Bull. 38, 1913.

[2] Inst. Min. Eng. [London] Trans., vol. 42, p. 2, 1911.

In all the specimens noted in the Paleozoic coal fields in the upper Mississippi Valley the substance retains its russet-amber, vitreous, translucent, resinous aspect, appearing exactly like some of the resins in the younger coals. One of the fragments from La Salle is slightly yellowish, granular, and more opaque than the others in the same fragment of coal. Another is somewhat irregularly pitted or hollowed, as is indistinctly shown in figure 1, Plate XI. The resin lumps in these coals are friable and have a conchoidal fracture. Fragments from the Indiana specimen illustrated in figure 2, Plate XI, when burned on the platinum spoon by Chase Palmer, of the Geological Survey, were found to fuse readily, gradually turning brown, while emitting resinous odors. At higher temperatures they became dark and pitchy, emitting resin fumes before bursting into a light-yellow flame. A trace of grayish ash remained on the platinum after combustion. A very small quantity of this resin examined by David T. Day was found to be hardly soluble in alcohol, though it was partly dissolved in chloroform.

As already remarked, no systematic search for resin in the Paleozoic coals of the eastern interior basin or any other Paleozoic region has been made. It is probable, however, that resins will be found to be widespread in those Paleozoic coals that are not too far altered, in accordance with the observations of the Tertiary and Cretaceous coals of corresponding rank. The amount of wound or surface-exudate resin secreted by the Paleozoic plant types appears to have been small compared with that secreted by the later plants, but it is probable that the Paleozoic plants had ample canal storage.

Regarding the probably resinous nature of the canal casts so abundant in many of the carbonized woods in the Paleozoic bituminous coals of the interior fields, as described and illustrated on previous pages, I have recently learned of criteria of a novel and interesting character.

The occurrence of Paleozoic fossil plants on Big Spring Creek, 20 miles southeast of Lewiston, Mont., having been reported, specimens were, at my request, gathered in 1911 by Dr. A. C. Peale, of the United States National Museum, with whom was associated Mr. A. C. Silberling. The material collected was found on examination to consist mostly of the remnants of very badly macerated fragments of ferns, lycopods, and Calamariæ, carbonized and confusedly mingled with sufficient extremely fine gray argillaceous silt not only to destroy its value as coal, but even to impart to some of the layers a soiled, dark, sooty gray color. Though petioles of several types are abundant in this material, no filicoid pinnules are distinguishable, they having apparently disappeared by decay. Carbonized stem fragments of Sphenophyllum, Asterophyllites, Calamites, and Lepidodendron are mingled with megaspore exines, sporangia, and seed coats of Cardiocarpon.

The strata of this vicinity are said by W. R. Calvert, who in 1911 made a reconnaissance examination of the geology of this part of Montana, to belong to the upper part of the Quadrant formation, the geologic age of which has been questioned. Numerous petioles, exhibiting the characteristic superficial features of *Sphenopteris* (*Lyginodendron*) *hoeninghausii*, associated with *Lepidodendron obovatum* in the collection show that at least this part of the Quadrant formation is of Pottsville (Westphalian) age.

On examining the fossils from Big Spring Creek I was greatly astonished to see flat bunches of parallel, flexible, threadlike fibrils, suggesting the raveled edge of some textile fabric, protruding from the edges of the rock and from the ends of some of the carbonized plant fragments. A close examination of these singular fibrils showed them to issue from the ends of carbonized fragments of certain narrow, slender stems or petioles, apparently of a filicoid type, that were most abundant in the coaly shale. The scalelike coaly residues of these petioles (as I prefer to regard them) are longitudinally traversed by the parallel fibrils, which are completely enveloped by the carbon, though between many of the fibrils the carbon, representing the remaining undestroyed substance of the petiole, is thinner than the diameter of a fibril; consequently the fibrils produce prominent ridges in the carbon. On account of the hardness and tenacity of the fibrils, they may not only be readily stripped from the carbonaceous matrix but some of them may be pulled in segments of considerable length from the broken edges of the shale. Segments over 8 centimeters in length may be obtained without great difficulty. The aspect and mode of occurrence of these most interesting features can, however, be best comprehended on examining the accompanying illustrations.

In the small fragment photographed natural size shown in figure 1, Plate XIII, is seen the carbonized residue of a petiole transversely crossing the shale fragment. The petiole evidently was much macerated and is now flattened to a very thin layer, less than 0.3 millimeter thick, of glistening black, imperfectly cubical but quite friable coal. This is longitudinally traversed by the parallel fibers, whose continuity and strength have enabled them to tear a part of the petiole, on the left, from the adjoining shale. This part of the petiole is now held suspended by the fibrils, which are still "in place." The appearance of the specimen is better shown in figure 1, Plate XIV, photographed twice the natural size. Obviously we have here the homologue of the needle-like casts of the canals already described as occurring in the flattened and reduced carbonized woods from the coals of the Mississippi Valley. However, in the Montana material, which is less altered, the fibrils are still somewhat flexible and tough. When the canal fillings are isolated the adhering fragments of coal and shale may be mostly removed by careful crushing or rubbing between the fingers, leaving the dark, threadlike casts free, whereupon, if long and unsupported, they are apt to droop slightly by their own weight, as shown in figure 3, Plate XIII, and figure 2, Plate XIV.

The parallelism and regularity of the canal casts and their relation to the carbonized residues, which often lie compactly superposed in varying directions, are better seen in figure 2, Plate XIII, which represents a thin layer of the shaly bone. Examination of the photographic enlargement of a part of the same specimen, shown in figure 3, Plate XIV, shows the casts to be nearly cylindrical, though slightly variable in cross section. Notwithstanding a degree of flexibility (see fig. 3, Pl. XIII), which enables the threadlike casts to be bent and twisted to a certain extent, and a toughness which enables one actually to pull them out to the edges of the shaly bone (so friable is the environing coaly scale), they are brittle, usually fracturing squarely, though minutely conchoidal. In many specimens the fragments of carbonaceous shale are, when broken, held together by the canal casts, as illustrated in figure 2, Plate XIV. In most of the petioles the maceration and decay of the plant tissues at the time of their deposition in the muddy water of the swamp were not so complete as to leave the casts without support. In other fragments, however, as illustrated in figure 4, Plate XIV, the decay extended to more resistant cortical tissues, so that the casts were left free and unsupported within the sheath maintained by the cuticle. This is shown not only by the nearly complete absence of environing coaly residue, but also by the lax, irregular attitudes of the released fillings of the canals, which curve and overlap in slight confusion, although their general longitudinal direction is preserved. Frequently the casts were entirely freed by the decay of the stems or petioles, so that they are left isolated and drifted about in various positions, as is shown in portions of the same figure. It is to be noted that the isolated and probably slightly drifted casts were at the time of the deposition of the plant débris so brittle that they were broken into fragments comparable to those of the isolated rods seen in the coals of Illinois, Iowa, Missouri, and Indiana, though in the Montana specimens they seem to have been slightly less friable and more flexible and are usually found in greater lengths where isolated and tangled in the surrounding clay or débris.

Like the secretions from the coals of the Mississippi Valley already described, the Montana rods appear amorphous, to the naked eye resembling vulcanized rubber. When freed from the surrounding carbon or adhering clay by gentle rubbing between the fingers or by treatment in hot nitric acid, the isolated threads may be manipulated with ease and mounted for examination under the microscope. They are then found to be composed of a russet-yellow, semitranslucent substance resembling resin. The thinner sections presented by the more slender threads approach an orange-yellow. It is to be noted also that many of the canals were, for apparently short distances, not completely filled by the substance, which seems to have been deposited on the walls so as to form a hollow cylinder. Some of the cylinders were crushed or caved in on one side. The attempt to discern the configuration of the contact cells forming the walls of the vessel has not yet been wholly successful, though some of the rods have the aspect of having been bounded by longitudinally short, small cells, roughly quadrilateral in outline. The evidence, so far as it goes, points, therefore, to the typical canal structure for the container of the resin-like secretion.

As previously noted, the canals varied considerably in diameter, some of the plants having comparatively large rods like those shown in figure 2, Plate XIII, and figure 3, Plate XIV, while in others, such as are seen in figure 1, Plate XIII, the rods are relatively slender. Some difference in size is to be observed even in the fibrils lying in a single petiole. In this connection it may be remarked that similar differences may be noted in the Myelopteris petioles described by Renault and Zeiller, previously mentioned.

The examination of the Montana material leaves scarcely room for doubt that it is of the same general nature as the secretions filling the canals in the carbonized woods or freed as needle-like fragments in the vegetable débris or carbonaceous muds of the Illinois coal field. It will have been noted that in both regions the fillings or rods were evidently approximately cylindrical in form and of nearly uniform diameter throughout great lengths; that most of them were hard enough successfully to resist the pressure of overlying vegetable débris and muds, not only during the peat-forming process, but also during later periods; that they appear to have been largely if not completely resistant to the biochemical processes which accomplished the partial decomposition and transformation of the vegetal débris into peat; and that they have survived the subsequent dynamic and chemical agencies which transformed the original peaty substance into a cubical laminated coal of low bituminous rank. The conditions of their release from the freshly rotting stems and petioles in the water of the peat-forming swamps and the mode of their deposition in the peat absolutely preclude all hypotheses explaining their origin as infiltrations of vessels or canals subsequent to the burial of the stems in the peat.

The isolated rods ignite readily and burn freely with a bright-yellow flame and a moderate amount of smoke in the open air, leaving a small amount of dark-gray residue. Small quantities of the threads, after isolation and such imperfect cleaning as could be given by moderate rubbing between the fingers, were, through the courtesy of Mr. J. D. Davis, of the Bureau of Mines, subjected by him to ultimate analysis, with the following result:

Analysis of resinous vessel casts from Montana.

C	72.69
H	8.85
O	13.61
Ash	4.85
Ash-free:	
C	76.40
H	9.30
O	14.30

It is probable that the ash of the sample is slightly high on account of the method of cleaning, which possibly also affected the other percentages to a slight extent, though presumably in no important way. Mr. Davis states that very little of the substance has been dissolved by acetone during about five months. The analysis of the Montana resinoid secretions may profitably be compared with some of the analyses given on page 68. It is particularly comparable to the analysis of the lump resins from the Upper Cretaceous coals in northern New Mexico, described by Loew[1] as wheelerite.

---

[1] Loew, Oscar, Am. Jour. Sci., 3d ser., vol. 7, p. 571, 1874. Specimens probably from the Cretaceous of northwestern New Mexico.

Analysis of wheelerite from New Mexico.

C	73.07
H	7.95
O	18.98

The highly "bituminous" character of the Montana Paleozoic material is conspicuously shown by its high "available" hydrogen ($H-\frac{O}{8}=7.5$ per cent) and its high hydrogen-oxygen ratio of 0.65, which, in a coal of the ordinary humic type, should place it within the coking class.[1] Obviously the effect of the presence of great numbers of these rods in a coal must be to "bituminize" it; to provide a high percentage of volatile matter; to impart a high calorific value to it; and, similarly, through the presence of so much hydrogen probably, to make the volatile highly illuminant. The rods are excellent cannel-forming ingredient matter.

In view of (1) the mode of occurrence of the secretions inclosed in the canals of the petioles and carbonized woods, as well as free in both the Montana and the eastern interior coal measures, (2) their resistance to the agencies of decay, (3) their aspect and state of preservation, (4) the microscopic characters of the substance composing the casts and its optical similarity to resin, (5) the close agreement, according to the chemical analysis, with the resins, and (6) the ascertained presence of lump resin in the Carboniferous coals of the upper Mississippi Valley, I have had little hesitation in regarding all these substances as resins, though not necessarily as identical resins. Not only is the Montana substance itself resin-like, but its mode of occurrence is a common mode of resin secretion in the plants of to-day. That it may be a gum seemed improbable, largely on account of its resistance to the agencies of alteration.

Feeling, however, that the Montana material, which is somewhat tougher and more elastic than the secretions found in the eastern coals (though it may not always have been so), might represent an unusual mode of occurrence of a resin-like wax rather than a typical resin, I submitted samples of the casts to Dr. C. L. Alsberg, then of the Bureau of Plant Industry in the Department of Agriculture, whose broad interest in problems of this kind and whose friendly courtesy prompted him to investigate the substance of the rods as thoroughly as the circumstances would permit. Dr. Alsberg's preliminary conclusion is that the substance from Montana is probably resinous. He says:

> The fibrils were carefully separated from the matrix and freed from the latter as much as possible by rubbing between the fingers and by brushing with a camel's-hair brush. They were apparently insoluble in cold and hot water, in cold and hot alcohol, in chloroform, toluene, benzol, and boiling concentrated hydrochloric acid. Hot concentrated sulphuric acid caused them to disintegrate into many smaller fibrils without much charring. Hot 10 per cent potassium hydroxide caused the fibrils to swell somewhat, to soften, and, to a slight extent, to dissolve. Boiling with concentrated nitric acid caused rapid solution of the black outer layer, with evolution of gas, leaving a reddish, transparent, soft core. When cold this core became hard and flexible again. After the black coating had been dissolved by the nitric acid, the core apparently resisted further attack by the acid.
>
> Thereupon 0.5537 gram was boiled with 95 per cent alcohol under a reflex condenser for several days. The material extracted weighed less than a milligram. The extraction was repeated with chloroform, which extracted but 2 milligrams. Then toluene was tried, yielding 1.2 centigrams of extracted material.
>
> Since so little of the material was soluble in these organic solvents it was treated with concentrated hot nitric acid till the black outer layer was removed. It was then washed with water till all the acid was removed and dried. It was next extracted with ether under the reflex condenser. A small amount passed into solution. The extraction was repeated until no more was dissolved. It was then extracted in the same manner with chloroform; but only traces of material were dissolved in the course of several days. Thereupon the material was extracted with alcohol, which dissolved appreciable quantities. In the course of several weeks the boiling alcohol extracted about one-third of the material. After the alcohol extracted nothing more, the extraction was continued with toluene, which extracted a small amount. The residue which remained was partially soluble in a concentrated solution of chlorohydrate.
>
> The different fractions into which the material was separated by these solvents are being investigated chemically. It is hoped that further data may in the future be published. At present from the data at hand it is possible to say that the indications are that the material is of a resinous nature. The solubilities point in this direction. Very few other substances have such solubilities. The solubility in chlorohydrate is particularly significant.

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[1] Bureau of Mines Bull. 29, p. 52, 1911.

CONCLUSIONS.

From the criteria reviewed it appears that at least a large part of the petioles and trunks of the Carboniferous coal-forming types of vegetation were provided, as described by several paleobotanists from petrified specimens, with numerous secretory canals and cells, in many of which residues, generally interpreted as gums but often suggesting resins and waxes, may still be seen. In the preceding pages evidence has been presented showing not only the presence of lump or exudate resins in Paleozoic coals of a somewhat low bituminous rank, but also the occurrence in these coals of great quantities of wood and petioles traversed by canals largely if not completely filled with secretions, whose mode of occurrence, optical characters, chemical composition, and resistance to decay under the conditions of coal formation seem to combine in proof of their resinous nature. These canal secretions were not only largely resistant to the biochemical processes of peat formation but they have withstood (though probably not without some chemical change) the ordinary dynamo-chemical processes of peat transformation, probably except contact metamorphism, until the coals attained at least a low bituminous rank. Their abundance in Paleozoic coals of this or lower ranks may readily be confirmed on close examination.

These resinous fillings have, as a result of the partial dehydration, the progressive chemical waste or reduction, and the pressure collapse of the environing undecayed plant tissues, been, in effect, concentrated in the coals, so that their proportionate volume is much increased even in the undestroyed wood. A great concentration results from the more advanced decay of the other plant tissues, so that the resinous rods or bodies are either separated only by extremely thin carbon residues representing the remaining portions of the plant, or they are completely freed and isolated and so permitted to lodge and accumulate, frequently in contact, in relatively large quantities. Such isolated resin fragments form a permanent and considerable ingredient of the coals of the cannel type, in some localities contributing largely to their physical and chemical qualities; and they are particularly characteristic of the canneloid fuels of the Cretaceous and Tertiary coal fields.

The amount of the wood and petioles probably containing resin found in the Paleozoic coal measures, both at the Montana locality and in the upper Mississippi Valley, justifies the conclusion that the quantity of resin contributed by the coal-forming plants and preserved either in place in the wood or as accumulations (concentrates) in various layers of the coal may, on the whole, have been as great in the Paleozoic era as in later epochs. Though the Paleozoic resins were probably secreted in lump or exudate form far less than the resins of the plants, especially the conifers, of the later formations, they were, I am inclined to believe, as important as contributions to the coal. Furthermore, it will be remembered that the aspect of the spore and pollen exines found in the coal, the characteristic features of the chemical analyses of the coal, and the fact that the exines have physically so far survived the decomposing agencies appear amply to sustain the belief that in both the Paleozoic and the Mesozoic plants the exines were, like their modern representatives, provided with protective wax, resin, and gum secretions. The amount of resinous and waxy material contributed by the highly varied and incredibly numerous spores in the Carboniferous coals was in itself undoubtedly large; and where, as in the cannel coals, such spores compose a large part of the fuel body, the resinous material, perhaps as much as the waxes, has produced the peculiar commercial and chemical qualities which characterize the coals of the cannel type. In this connection it may be remarked that some of the pinnules of cycadofilic types—such, for example, as *Neuropteris flexuosa* of the upper Pottsville or *Neuropteris gigantea* of the middle Pottsville—were probably provided with waxy coverings analogous to those borne by many leaves among living plants.

It is probable that in the Paleozoic as well as in the Cenozoic era many among the coal-forming species were not resin-producing, for many of the associated wood and petiole fragments found in the coal show no megascopic indications of such secretions. In the Montana material the resinous threads seem to be confined to petioles or slender stems, which, from the differences in the sizes of the canals, were presumably of more than one genus and species. At the Montana locality the resin-bearing plants, whether or not of several kinds, were very abundant, probably forming the larger part of the arborescent material contributed to the coaly shales at certain levels. There is reason to believe that in the Paleozoic, as in the later epochs, the resins produced by different plants varied in composition and qualities.

The evidence offered by the American material makes it seem not improbable that the dark-brown residues found in the canals of the silicified material from the French Permian also is resinous, as was suggested by Renault and Zeiller. The unquestionable presence of lump resin in the Paleozoic coals of the upper Mississippi Valley argues strongly also for the resinous nature of the dark contents of the secretory cells and canals of some of the other plants found petrified in the Carboniferous of Europe.[1]

The analogies to be drawn from the deformation, discoloration, alteration, and reduction (carbonization, involving loss of volatile) of the megascopic resin lumps as the coals of the Cretaceous and Tertiary in Colorado and Washington were brought from the lower-bituminous to the higher-bituminous ranks appear to offer a reasonable explanation for the failure hitherto to observe lump resin in the higher-rank bituminous coals of the Appalachian trough and for the probable absence of canal resin casts in the semibituminous coals of the same province. The question as to the extent of their survival (without doubt they were once present) in the areas of high-rank coal remains to be determined by observation, though it is probable that they are present in some of the lower-rank coals having a fixed carbon ("pure coal" basis) of less than 58 or 55 per cent in the western portion of the great Allegheny coal field.

A question which appears to deserve careful consideration is, What relation, if any, may the alteration or transformation (natural distillation) of these high-hydrogen and high-volatile fusible elements of the coals which appears to take place in a critical period (limited in round terms by the passage from 58 to 65 per cent of fixed carbon in "pure coal"), as the fuels are being brought by the dynamo-chemical agencies to the state of fitness, other things being equal, for the production of high-grade coke by the ordinary process, bear to the development of the coking quality itself in the coals?

---

[1] The superficial aspect of the Montana petioles, the characters of their finely striated cuticles, and their mode of branching strongly suggest the petioles of Alethopteris and Neuropteris, to which I believe them probably to have belonged. The slightly irregular but generally parallel longitudinal lineation of the carbonized residues was presumably produced by hypodermal strands of thick-walled and slightly more resistant tissue, distributed mainly in a subperipheral zone. The secretory canals were most probably associated with such hypodermal strands, very much or perhaps identically as in the petrified stems described by Renault (Acad. sci. Paris Mém. sav. étrang., vol. 22, No. 10, p. 17, Pl. V, fig. 10, 1875) and Zeiller (Bassin houiller et permien d'Autun et d'Épinac, vol. 1, Flore fossile, pt. 1, Pl. XXVII, fig. 2, 1890) as Myelopteris and Myeloxylon.

PLATE IX.

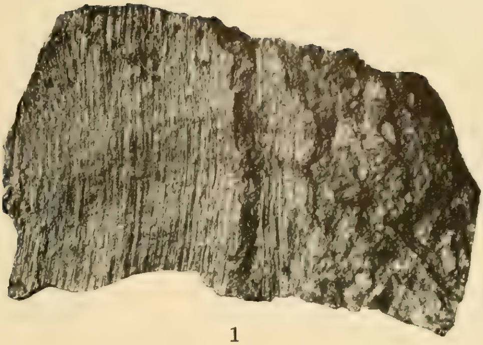
PLATE IX.

FRAGMENTS OF BITUMINOUS COAL SHOWING CARBONIZED WOOD, ETC.

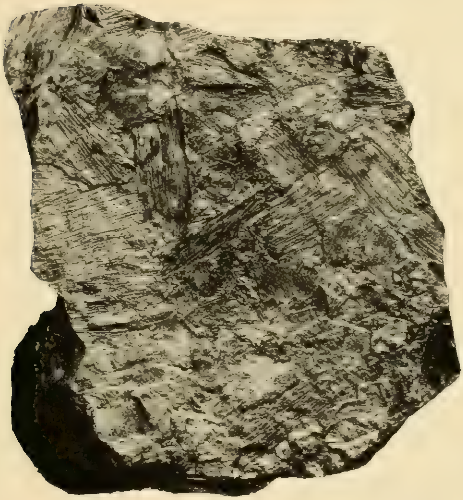
FIGURE 1. Portion (natural size) of a large fragment of wood from the midst of the coal mined at Gerlaw, Ill. The wood, which is flattened comparatively thin, is traversed, parallel to the grain, by very slender needle-like casts, the remains of hard secretions, regarded as resinous, occupying the longitudinal canals. On the right are fragments of bark, cuticles, and small miscellaneous vegetal débris, all carbonized. A portion of the same specimen is shown four times enlarged in Plate XI, figure 4.

FIGURE 2. Bedding-plane surface (natural size) of a block of coal from a mine in "coal No. 2," near Exeter, Ill. The surface is strewn with small pieces of wood now flattened and converted to mineral charcoal ("mother of coal"). Most of the pieces are traversed lengthwise of the grain by needle-like resinous canal casts, like those shown in figure 1, but much more slender. A part of this specimen is shown four times enlarged in Plate X.

FIGURE 3. Fragment (natural size) from a thin parting in the coal (No. 2) at Colchester, Ill., showing the very slender needle-like resin fillings of the canals, released by the decay of the surrounding tissues of the wood and now drifted in confusion. On the same specimen, as shown in bedding-plane view four times enlarged in Plate XII, are many megaspores and several envelopes of seeds all representing vegetal tissues most resistant to decay. Small particles of cuticle are also present.



1



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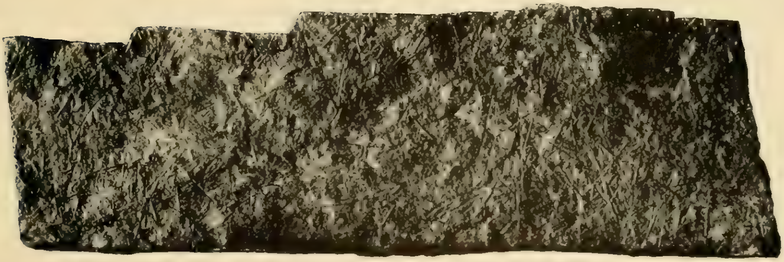


3

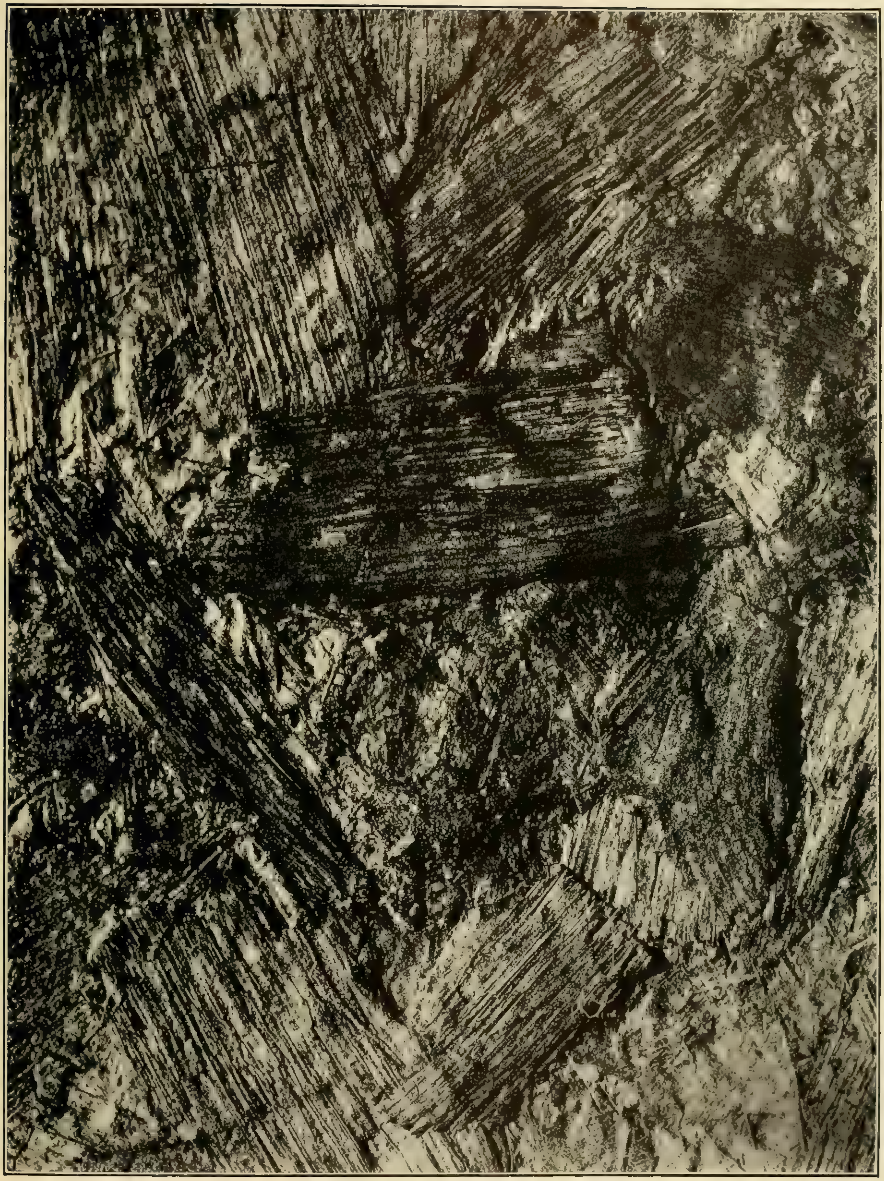
FRAGMENTS OF BITUMINOUS COAL SHOWING CARBONIZED WOOD, ETC.

PLATE X.

PLATE X.

BEDDING PLANE OF COAL FROM EXETER, ILL.

A portion of the block shown in Plate IX, figure 2, four times the natural size. The resinous casts of the canals longitudinally traversing the fragments of carbonized wood appear like needles or fine wires lying parallel to the surface or protruding obliquely and at the ends of the pieces of wood. In some places the wood has rotted so that the casts are left entirely freed and isolated. The surrounding wood cells were so macerated and compressed that many of the slender round casts stand out as ridges in the coaly residue even where they are not actually exposed.



BEDDING PLANE OF COAL FROM EXETER, ILL.

PLATE XI.

PLATE XI.

RESIN LUMPS IN PALEOZOIC COALS.

FIGURE 1. End view (five times enlarged) of a piece of coal from shaft at La Salle, Ill., showing a cross section of a flattened lump of rather dark amber-like resin. It is slightly pitted.

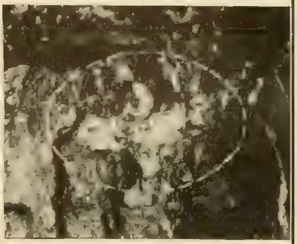
FIGURE 2. End view (five times enlarged) of a fragment of "block" coal from a mine near Brazil, Ind., showing a lump of resin. The resin has been squeezed both along the bedding plane and in the joints, so that its cross section exhibits a zigzag or "step" form. The light-colored spots above and below are mere reflections from fracture surfaces of the dense laminated coal, the photograph not being retouched. Fragments of the lump here shown have been subjected to combustion and chemical tests.

FIGURE 3. Another lump (five times enlarged) found on another side of the block of coal shown in figure 2. The lump is somewhat squeezed but retains its typical "rosin"-like translucent character. The outline of the section is crescentic, convex downward; the apparent extensions above and below are reflections from cleavage planes in the coal. The photograph is not retouched. The same specimen of coal exhibits a third resin lump.

FIGURE 4. Portion (four times enlarged) of the fragment from Gerlaw, Ill., shown in Plate IX, figure 1, showing the needle-like casts or resinous fillings of the canals in the wood, the grain of which runs vertically in the picture. The casts are in some places fully exposed, in others are protruding and broken off, and in still others appear only as ridges in the thin layer of mineral charcoal to which the wood is reduced.

1

2



3

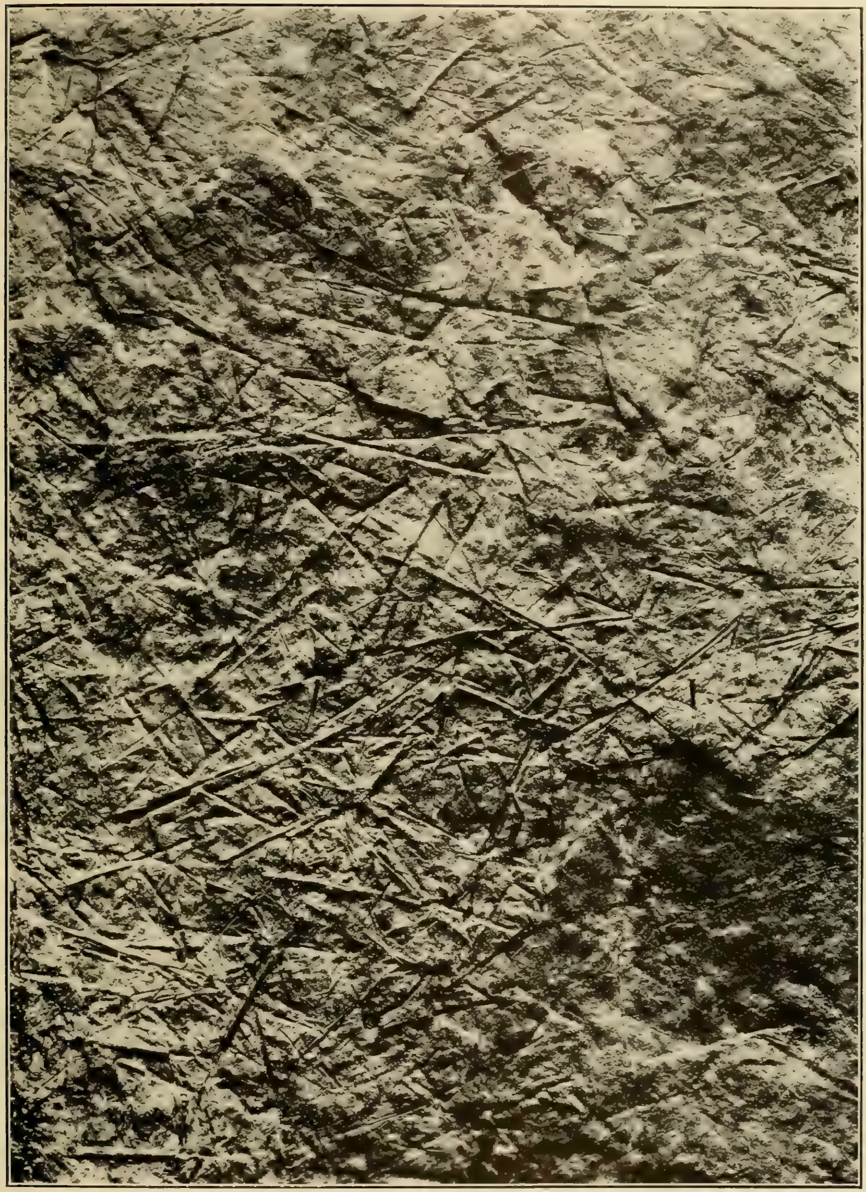
RESIN LUMPS IN PALEOZOIC COALS.

PLATE XII.

PLATE XII.

FRAGMENT FROM THIN PARTING IN COAL FROM COLCHESTER, ILL.

Portion (four times enlarged) of the very thin parting shown in bedding-plane view in Plate IX, figure 3. Shows the round, slender, needle-like resinous casts from the canals of various woods. The casts, freed by the decay of the other tissues of the wood, have accumulated in great numbers, effecting a concentration of the resin substance. Fragments of cuticle, spore exines, and seed coats are also present.



FRAGMENT FROM THIN PARTING IN COAL FROM COLCHESTER, ILL.

PLATE XIII.

PLATE XIII.

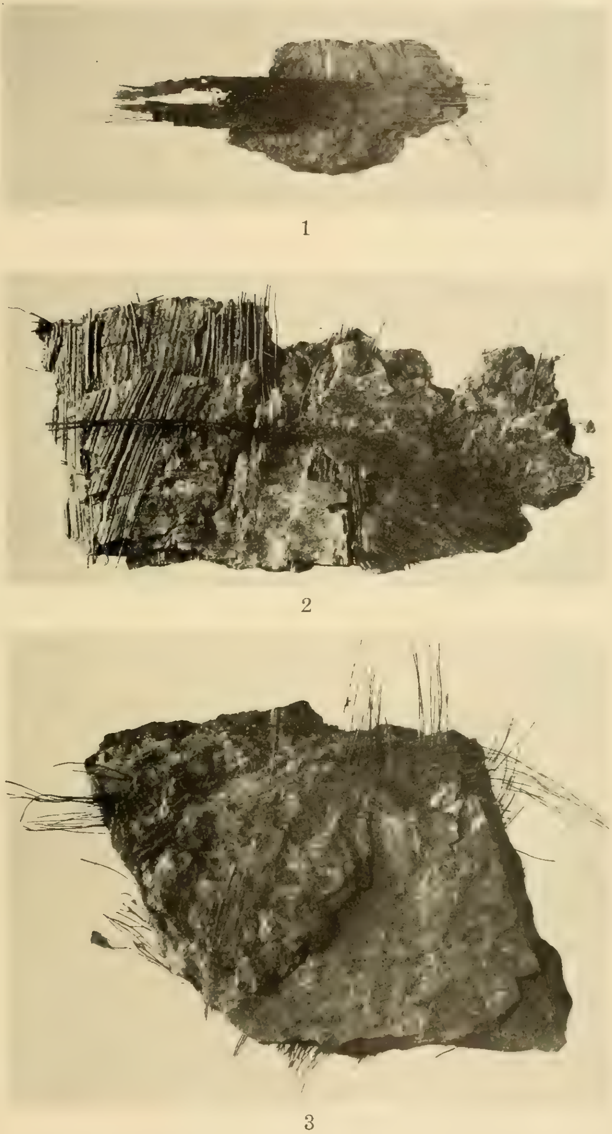
Resinous casts in stems or petioles.

[From Big Spring Creek, 20 miles southeast of Lewiston, Mont. Quadrant formation; Pottsville age.]

Figure 1. Fragment of coaly shale crossed by the thin carbonized residue of a petiole, a portion of which (on the left) is held suspended by the very slender, threadlike resinous casts, which protrude at the ends like bristles or fibrils. The same specimen is shown twice enlarged in Plate XIV, figure 1.

Figure 2. Fragment of dark shaly coal or coaly shale, in which many of the petioles (or stems ?) are matted in various directions. The resinous casts of the canals, some of which are very large, make ridges in the very thin carbonized residues of the petioles, even where they are still enveloped by the coalified flattened remains of the surrounding tissue of the wood or bark. At several points casts isolated by the decay of the wood are seen. A portion of this specimen is shown twice enlarged in Plate XIV, figure 3.

Figure 3. Fragment of coaly shale from the edges of which protrude the parallel threadlike resinous vessel casts which have been pulled out of the carbonaceous residues in the adjoining fragments. The bands of casts lie in many directions and at many levels, according to the position of the containing carbonized wood.



RESINOUS CASTS IN STEMS OR PETIOLES.

PLATE XIV.

PLATE XIV.

THREADLIKE RESINOUS CASTS IN CARBONIZED WOODS.

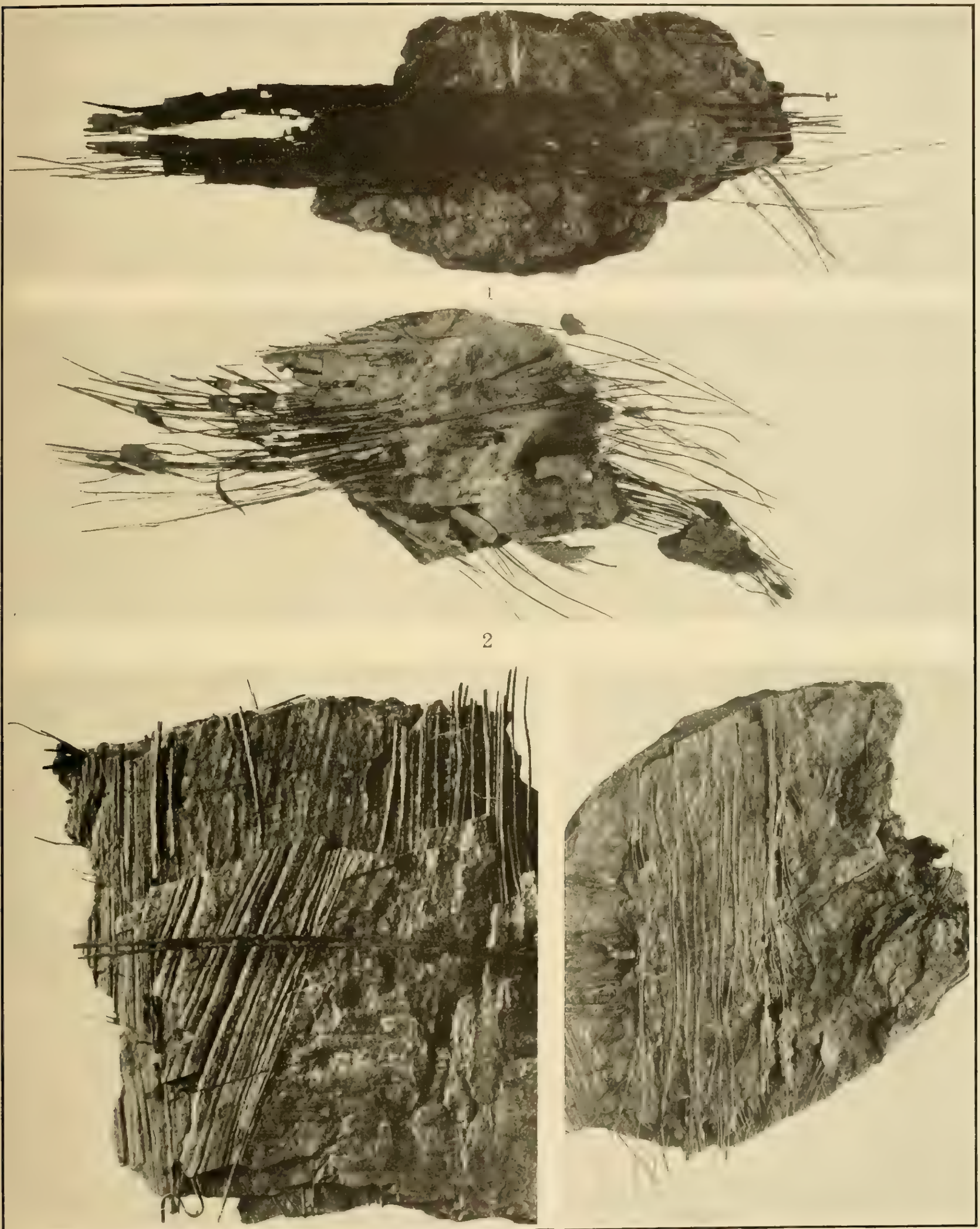
[From Big Spring Creek, 20 miles southeast of Lewiston, Mont. Quadrant formation; Pottsville age.]

FIGURE 1. Specimen shown in Plate XIII, figure 1 (enlarged two diameters), showing the cubical coal made from the remaining tissues of the petiole. The residue, which is less than 0.3 millimeter in diameter, is scarcely thicker than the resinous fibrils themselves. The cubically jointed coal has been lifted from the matrix and extends, sustained by the casts, on the left. Other stem fragments with casts lie in the same piece of coaly shale.

FIGURE 2. Fragment (twice natural size) in which the resinous casts, much greater in diameter, lie mostly in their original attitudes, the coal and mud having been partly removed.

FIGURE 3. Part of the specimen shown in Plate XIII, figure 2 (twice natural size), showing the parallelism and aspect of the resin canal casts, which in some of the petiolar fragments are very large. Regarding the relative diameter of the canals, compare this figure with a corresponding enlargement given as figure 1 above.

FIGURE 4. Piece of the coaly shale transversely crossed by a petiole or small stem which before burial in the carbonaceous mud had so far rotted that the resinous casts of the canals were left free and unsupported by intervening woody tissues. They lie longitudinally extended but lax and irregularly disposed within the thin outer sheath of the petiole. Many cast fragments wholly isolated by the decay of their enveloping stems are scattered in the richly carbonaceous mud.



THREADLIKE RESINOUS CASTS IN CARBONIZED WOODS.

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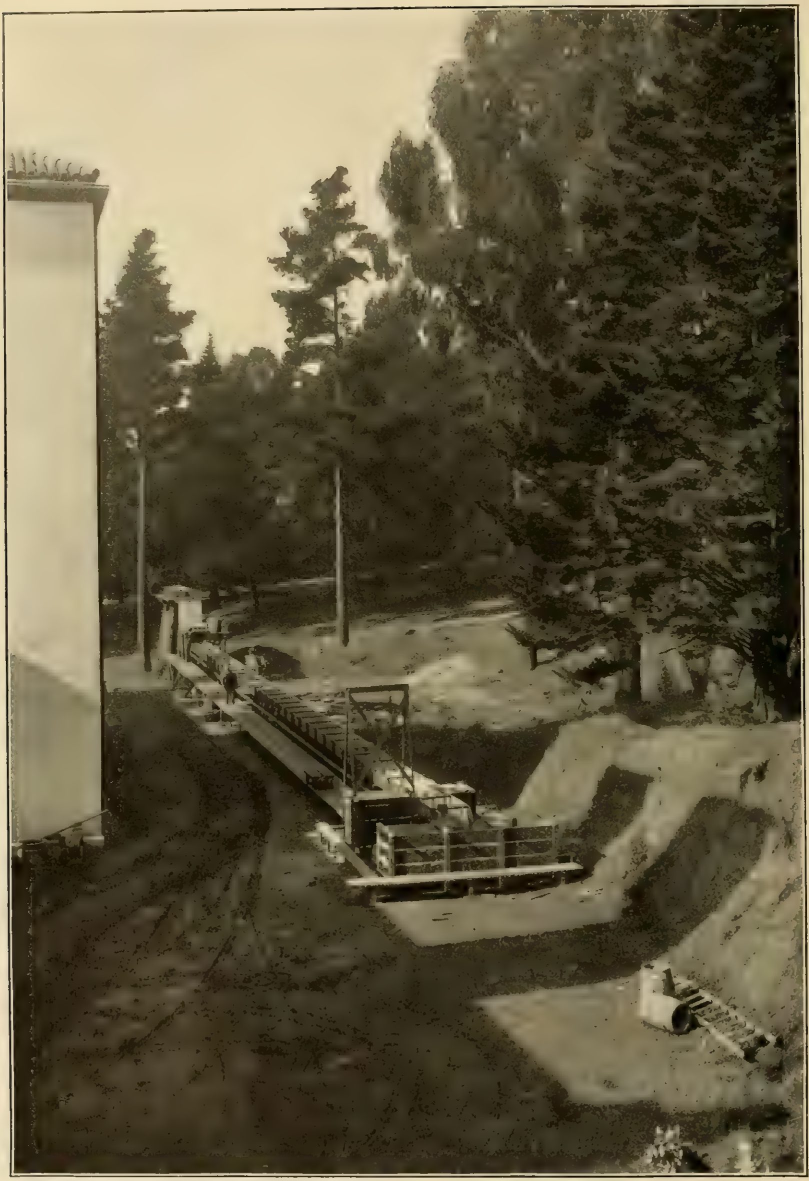

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THE
TRANSPORTATION OF DÉBRIS BY RUNNING WATER

BY

GROVE KARL GILBERT

BASED ON EXPERIMENTS MADE WITH THE ASSISTANCE OF

EDWARD CHARLES MURPHY

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PREFACE.

Thirty-five years ago the writer made a study of the work of streams in shaping the face of the land. The study included a qualitative and partly deductive investigation of the laws of transportation of débris by running water; and the limitations of such methods inspired a desire for quantitative data, such as could be obtained only by experimentation with determinate conditions. The gratification of this desire was long deferred, but opportunity for experimentation finally came in connection with an investigation of problems occasioned by the overloading of certain California rivers with waste from hydraulic mines. The physical factors of those problems involve the transporting capacity of streams as controlled by various conditions. The experiments described in this report were thus instigated by the common needs of physiographic geology and hydraulic engineering.

A laboratory was established at Berkeley, Cal., and the investigation became the guest of the University of California, to which it is indebted not only for space, within doors and without, but for facilities of many kinds most generously contributed.

Almost from the beginning Mr. E. C. Murphy has been associated with me in the investigation and has had direct charge of the experiments. Before the completion of the investigation I was compelled by ill health to withdraw from it, and Mr. Murphy not only made the remaining series of experiments, so far as had been definitely planned, but prepared a report. This report did not include a full discussion of the results but was of a preliminary nature, it being hoped that the work might be continued, with enlargement of scale, in the near future. When afterward I found myself able to resume the study, there seemed no immediate prospect of resuming experimentation, and it was thought best to give the material comparatively full treatment. It will readily be understood from this account that I am responsible for the planning of the experimental work as well as for the discussion of results here contained, while Mr. Murphy is responsible for the experimental work. It must not be understood, however, that in assuming responsibility for the discussion I also claim sole credit for what is novel in the generalizations. Many conclusions were reached by us jointly during our association, and others were developed by Mr. Murphy in his report. These have been incorporated in the present report, so far as they appeared to be sustained by the more elaborate analysis, and specific credit is given only where I found it practicable to quote from Mr. Murphy's manuscript.

Mr. J. A. Burgess was for a short time a scientific assistant in the laboratory, and his work is described in another connection. Credit should be given to Mr. L. E. Eshleman, carpenter, and Mr. Waldemar Arntzen, mechanician, for excellent work in the construction of apparatus. I recall with sincere gratitude the cordial cooperation of several members of the university faculty, and the investigation is especially indebted to the good offices and technical knowledge of Prof. S. B. Christy and Prof. J. N. Le Conte.

Portions of my manuscript were read by Dr. R. S. Woodward and Dr. Lyman J. Briggs, and the entire manuscript was read by Mr. C. E. Van Orstrand and Mr. Willard D. Johnson. To these gentlemen and to members of the editorial staff of the Geological Survey I am indebted for criticisms and suggestions leading to the elimination of some of the crudities of the original draft.

While the aid which my work has received from many colleagues has been so kindly and efficient that individual mention seems invidious, my gratitude must nevertheless be expressed for valuable assistance by Mr. François E. Matthes in the examination of foreign literature, and for the unfailing encouragement and support of Mr. M. O. Leighton, until recently in charge of the hydrographic work of the Survey.

G. K. G.

ABSTRACT.

Scope.—The finer débris transported by a stream is borne in suspension. The coarser is swept along the channel bed. The suspended load is readily sampled and estimated, and much is known as to its quantity. The bed load is inaccessible and we are without definite information as to its amount. The primary purpose of the investigation was to learn the laws which control the movement of bed load, and especially to determine how the quantity of load is related to the stream's slope and discharge and to the degree of comminution of the débris.

Method.—To this end a laboratory was equipped at Berkeley, Cal., and experiments were performed in which each of the three conditions mentioned was separately varied and the resulting variations of load were observed and measured. Sand and gravel were sorted by sieves into grades of uniform size. Determinate discharges were used. In each experiment a specific load was fed to a stream of specific width and discharge, and measurement was made of the slope to which the stream automatically adjusted its bed so as to enable the current to transport the load.

The slope factor.—For each combination of discharge, width, and grade of débris there is a slope, called competent slope, which limits transportation. With lower slopes there is no load, or the stream has no capacity [1] for load. With higher slopes capacity exists; and increase of slope gives increase of capacity. The value of capacity is approximately proportional to a power of the excess of slope above competent slope. If S equal the stream's slope and σ equal competent slope, then the stream's capacity varies as $(S-\sigma)^n$. This is not a deductive, but an empiric law. The exponent n has not a fixed value, but an indefinite series of values depending on conditions. Its range of values in the experience of the laboratory is from 0.93 to 2.37, the values being greater as the discharges are smaller or the débris is coarser.

The discharge factor.—For each combination of width, slope, and grade of débris there is a competent discharge, κ. Calling the stream's discharge Q, the stream's capacity varies as $(Q-\kappa)^o$. The observed range of values for o is from 0.81 to 1.24, the values being greater as the slopes are smaller or the débris is coarser. Under like conditions o is less than n; or, in other words, capacity is less sensitive to changes of discharge than to changes of slope.

The fineness factor.—For each combination of width, slope, and discharge there is a limiting fineness of débris below which no transportation takes place. Calling fineness (or degree of comminution) F and competent fineness ϕ, the stream's capacity varies with $(F-\phi)^p$. The observed range of values for p is from 0.50 to 0.62, the values being greater as slopes and discharges are smaller. Capacity is less sensitive to changes in fineness of débris than to changes in discharge or slope.

The form factor.—Most of the experiments were with straight channels. A few with crooked channels yielded nearly the same estimates of capacity. The ratio of depth to width is a more important factor. For any combination of slope, discharge, and fineness it is possible to reduce capacity to zero by making the stream very wide and shallow or very narrow and deep. Between these extremes is a particular ratio of depth to width, ρ, corresponding to a maximum capacity. The values of ρ range, under laboratory conditions, from 0.5 to 0.04, being greater as slope, discharge, and fineness are less.

Velocity.—The velocity which determines capacity for bed load is that near the stream's bed, but attempts to measure bed velocity were not successful. Mean velocity was measured instead. To make a definite comparison between capacity and mean velocity it is neces-

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[1] *Capacity* is defined for the purposes of this paper as the maximum load of a given kind of débris which a given stream can transport. See page 35.

sary to postulate constancy in some accessory condition. If slope be the constant, in which case velocity changes with discharge, capacity varies on the average with the 3.2 power of velocity. If discharge be the constant, in which case velocity changes with slope, capacity varies on the average with the 4.0 power of velocity. If depth be the constant, in which case velocity changes with simultaneous changes of slope and discharge, capacity varies on the average with the 3.7 power of velocity. The power expressing the sensitiveness of capacity to changes of mean velocity has in each case a wide range of values, being greater as slope, discharge, and fineness are less.

Mixtures.—In general, débris composed of particles of a single size is moved less freely than débris containing particles of many sizes. If fine material be added to coarse, not only is the total load increased but a greater quantity of the coarse material is carried.

Modes of transportation; movement of particles.—Some particles of the bed load slide; many roll; the multitude make short skips or leaps, the process being called saltation. Saltation grades into suspension. When particles of many sizes are moved together the larger ones are rolled.

Modes of transportation; collective movement.—When the conditions are such that the bed load is small, the bed is molded into hills, called dunes, which travel downstream. Their mode of advance is like that of eolian dunes, the current eroding their upstream faces and depositing the eroded material on the downstream faces. With any progressive change of conditions tending to increase the load, the dunes eventually disappear and the débris surface becomes smooth. The smooth phase is in turn succeeded by a second rhythmic phase, in which a system of hills travel upstream. These are called antidunes, and their movement is accomplished by erosion on the downstream face and deposition on the upstream face. Both rhythms of débris movement are initiated by rhythms of water movement.

Application of formulas.—While the principles discovered in the laboratory are necessarily involved in the work of rivers, the laboratory formulas are not immediately available for the discussion of river problems. Being both empiric and complex, they will not bear extensive extrapolation. Under some circumstances they may be used to compare the work of one stream with that of another stream of the same type, but they do not permit an estimate of a river's capacity to be based on the determined capacities of laboratory streams. The investigation made an advance in the direction of its primary goal, but the goal was not reached.

Load versus energy.—The energy of a stream is measured by the product of its discharge (mass per unit time), its slope, and the acceleration of gravity. In a stream without load the energy is expended in flow resistances, which are greater as velocity and viscosity are greater. Load, including that carried in suspension and that dragged along the bed, affects the energy in three ways. (1) It adds its mass to the mass of the water and increases the stock of energy pro rata. (2) Its transportation involves mechanical work, and that work is at the expense of the stream's energy. (3) Its presence restricts the mobility of the water, in effect increasing its viscosity, and thus consumes energy. For the finest elements of load the third factor is more important than the second; for coarser elements the second is the more important. For each element the second and third together exceed the first, so that the net result is a tax on the stream's energy. Each element of load, by drawing on the supply of energy, reduces velocity and thus reduces capacity for all parts of the load. This principle affords a condition by which total capacity is limited. Subject to this condition a stream's load at any time is determined by the supply of débris and the fineness of the available kinds.

Flume transportation.—In the experiments described above—experiments illustrating stream transportation—the load traversed a plastic bed composed of its own material. Other experiments were arranged in which the load traversed a rigid bed, the bottom of a flume. Capacities are notably larger for flume transportation than for stream transportation, and their laws of variation are different. Rolling is an important mode of progression. For rolled particles the capacity increases with coarseness, for leaping particles with fineness. Capacity increases with slope and usually with discharge also, but the rates of increase are less than in stream transportation. Capacity is reduced by roughness of bed.

Vertical velocity curve.—The vertical distribution of velocities in a current is controlled by conditions. The level of maximum velocity may have any position in the upper three-fourths of the current. In loaded streams its position is higher as the load is greater. In unloaded streams its position is higher as the slope is steeper, as the discharge is greater, and as the bed is rougher.

Pitot tube.—The constant of the Pitot velocity gage—the ratio between the head realized and the theoretic velocity head—is not the same in all parts of a conduit, being less near the water surface and greater near the bottom or side of the conduit.

NOTATION.

Certain letters are used continuously in the volume as symbols for quantities, a definition accompanying the first use. These are arranged alphabetically in the following list, with brief characterization and page reference. The list does not include letters used temporarily as symbols and defined in immediate connection with their use; and if the same letter has both temporary and continuous uses only the continuous use is here given.

		Page.
A	A constant of the Pitot-Darcy gage.	254
(A), (B), etc.	Grades of débris, separated by sieves	21
(A_1 G_4), etc.	Mixtures of débris grades, the letters and figures indicating components and proportions	169
a	A pressure constant (Lechalas)	193
α	Numerical constant in equation $C=b_2(1-\alpha R)R^m$	125
Accents (´ ` ^ ˇ)	An accent over the symbol of a variable indicates the nature of its influence on a function. Thus $A=f(\acute{B}, \grave{C}, \hat{D}, \check{E})$ states that A is an increasing function of B, a decreasing function of C, a maximum function of D, and a minimum function of E	96
b	A constant in equation (109)	191
b'	A constant depth in equation (21)	88
b_1	A constant capacity in equation (10)	64
b_2	A constant capacity in equation (54)	129
b_3	A constant in equation (64)	139
b_4	A constant in equation (75)	151
b_5	A constant in equation (91)	186
C	Capacity of a stream for traction of débris (in gm./sec.)	35
C_r	Readjusted value of capacity	141, 151
c	Constant coefficient in $y=cx^j$	99
c_1	Constant coefficient in $C=c_1S^{j_1}$	109
D	Mean diameter (in feet) of particles of débris	21
d	Depth of current (in feet)	33
d	Differential	97
E	Efficiency of stream for traction of débris; capacity per unit discharge per unit slope; C/QS	36
ϵ	Base of Naperian logarithms	61
F	Linear fineness of débris; the reciprocal of D	21, 183
F_2	Bulk fineness of débris; the number of particles in a cubic foot	21, 183
ft./sec	Feet per second; unit of velocity	34
ft.^{3}/sec	Cubic feet per second; unit of discharge	34
g	Acceleration of gravity	225
gm./sec	Grams per second; unit of load and of capacity for load	34
H	Range of fineness	96
H, H_1	Readings of comparator, Pitot-Darcy gage	254
I	Synthetic index of relative variation	99
I_1	I for capacity and slope	122
I_3	I for capacity and discharge	147
I_4	I for capacity and fineness	153
I_{ds}	I for capacity and depth, slope being constant	164
I_{dQ}	I for capacity and depth, discharge being constant	164
I_{dv}	I for capacity and depth, mean velocity being constant	164
I_e	I for efficiency and slope	122
I_R	I for capacity and slope, form ratio being constant	119
I_V	I for capacity and mean velocity	157
I_{VS}	I for capacity and mean velocity, slope being constant	157
I_{VQ}	I for capacity and mean velocity, discharge being constant	157
I_{Vd}	I for capacity and mean velocity, depth being constant	157
I_w	I for capacity and slope, width being constant	119
i	Index of relative variation; exponent in $y=cx^i$	99
i_1	i for capacity and slope	99
i_2	i for capacity and form ratio	130
i_3	i for capacity and discharge	141
i_4	i for capacity and fineness	153
j	Exponent in $y=cx^j$	99
j_1	Exponent in $C=c_1S^{j_1}$	109
K, k	Constants of the Pitot-Darcy gage	254
κ	A constant discharge, corresponding to competent discharge	139
L	Length, as a dimension of units	139
L	Load; mass of débris transported through a cross section per unit time (in gm./sec.)	35
M	Mass, as a dimension of units	139

		Page.
m	Exponent in $C=b_2(1-\alpha R)R^m$	129
m_1	Exponent; $=m+1$	128, 129
n	Exponent in $C=b_1(S-\sigma)^n$	61, 64, 96
n_1	Exponent in $d=\frac{b'}{S^{n_1}}$	88
o	Exponent in $C=b_3(Q-\kappa)^o$	139
p	Exponent in $C=b_4(F-\phi)^p$	151
p. e	Probable error	89
π	Ratio of circumference of circle to diameter	21
ϕ	A constant linear fineness, corresponding to competent fineness.	151
Q	Discharge (in ft.^{3}/sec.)	35
R	Form ratio; d/w	36
ρ	Value of R corresponding to maximum capacity	129
S	Slope, in per cent, of stream bed or water surface	34
s	Slope of stream bed or water surface; $=$fall per unit distance.	34
σ	A constant slope, corresponding to competent slope	64
Σ	Sum of	228
T	Time, as a dimension of units	139
U	Duty of water (in gm./sec.) for traction of débris; capacity per unit discharge; C/Q	36
V	Velocity of current (in ft./sec.)	163
V_b	Velocity of stream at contact with bed (Lechalas)	193
V_m	Mean velocity; discharge$\div$area of cross section; Q/dw	33, 94, 155
V_s	Velocity of stream at surface (Lechalas)	194
v	Variable coefficient in $y=vx^i$	99
v_1	Variable coefficient in $C=v_1S^{i_1}$	99
v_3	Variable coefficient in $C=v_3Q^{i_3}$	141
w	Width of stream channel (in feet)	67

THE TRANSPORTATION OF DÉBRIS BY RUNNING WATER.

By Grove Karl Gilbert.

CHAPTER I.—THE OBSERVATIONS.

INTRODUCTION.

GENERAL CLASSIFICATION.

Streams of water carry forward débris in various ways. The simplest is that in which the particles are slidden or rolled. Sliding rarely takes place except where the bed of the channel is smooth. Pure rolling, in which the particle is continuously in contact with the bed, is also of small relative importance. If the bed is uneven, the particle usually does not retain continuous contact but makes leaps, and the process is then called *saltation*, an expressive name introduced by McGee.[1] With swifter current leaps are extended, and if a particle thus freed from the bed be caught by an ascending portion of a swirling current its excursion may be indefinitely prolonged. Thus borne it is said to be suspended, and the process by which it is transported is called *suspension*. There is no sharp line between saltation and suspension, but the distinction is nevertheless important, for it serves to delimit two methods of hydraulic transportation which follow different laws. In suspension the efficient factor is the upward component of motion in parts of a complex current. In other transportation, including saltation, rolling, and sliding, the efficient factor is the motion parallel with the bed and close to it. This second division of current transportation is called by certain French engineers *entraînement* but has received no name in English. Being in need of a succinct title, I translate the French designation, which indicates a sweeping or dragging along, by the word *traction*, thus classifying hydraulic transportation as (1) hydraulic suspension and (2) hydraulic traction.

The bed of a natural stream which carries a large load of débris is composed of loose grains identical in character with those transported. The material of the load is derived from and returned to the bed, and the surface of the bed is molded by the current. When débris is transported through artificial channels, such as flumes and pipes, the bed is usually rigid and unyielding. Trifling as this difference appears, it yet occasions a marked contrast in the quantitative laws of transportation, and in the laboratory the two kinds of transportation were the subjects of separate courses of experimentation. It is necessary, therefore, for present purposes, to base a second classification of hydraulic transportation on the nature of the bottom. As the bed is typically plastic in stream channels and typically rigid in flumes and other artificial channels, it is convenient to call the two classes *stream transportation* and *flume transportation*.

The second classification traverses the first and their combination gives four divisions—stream suspension, stream traction, flume suspension, and flume traction. This report treats of stream traction and flume traction. It contains the record and discussion of a series of experiments made in a specially equipped laboratory at the University of California, Berkeley, in the years 1907–1909.

STREAM TRACTION.

Previous to the Berkeley work little was known of the quantitative laws of stream traction. The quantity of material transported has sometimes been said to be proportional to the square of the slope, but I have failed to discover that the statement has a recorded basis in theory or observation. A statement more frequently encountered is to the effect that the quantity varies with the sixth power of the velocity; and the origin of this assertion is not in doubt. It is an erroneous version of a deductive law commonly attributed to Hopkins (1844) or Airy and Law (1885), although announced as early as 1823 by Leslie.[1] The law, as formulated by Hopkins, is that "the moving force of a current, estimated by the volume or weight of the masses of any proposed form which it is capable of moving, varies as the sixth power of the velocity"; and this law pertains not at all to the quantity of material moved, but to the maximum size of the grain or pebble or bowlder a given current is competent to move.

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[1] McGee, W J, Geol. Soc. America Bull., vol. 19, p. 199, 1908.

The subject of the competence of currents, or the relation of velocities to the size of particles they can move, has also been treated experimentally by several investigators, and some account of their work will be given in later chapters.

About the year 1883 Deacon made, in Manchester, England, a notable series of experiments in the field of stream traction. As a result of definite measurements of quantities of sand transported and of the velocities of the transporting currents, he announced [2] that the amount transported, instead of varying with the sixth power of the velocity, as had been supposed, actually varies with the fifth power.

In the field of flume traction the work has been somewhat more extensive, having as its special incentive the needs arising in ore mills for the conveyance of crushed rock; and a résumé of results will be found in the chapter on flume traction.

A still greater body of investigation has been conducted by German and French engineers with the use of laboratory models of river channels. The French work was done largely for the purpose of testing certain rules formulated by Fargue [3] for the improvement of navigable streams. The German experiments were and still are addressed to the broader subject of river engineering in general and include within their scope the scientific study of the ways in which rivers shape and reshape their channels. The quantitative laws of stream traction, which constitute the chief theme of the Berkeley work, thus fall within the province of the German investigators, but their study has not been taken up. There are three German laboratories, all well equipped, located severally at Dresden, Karlsruhe, and Berlin.[4]

The flow of a stream is a complex process, involving interactions which have thus far baffled mechanical analysis. Stream traction is not only a function of stream flow but itself adds a complication. Some realization of the complexity may be achieved by considering briefly certain of the conditions which modify the capacity of a stream to transport débris along its bed. Width is a factor; a broad channel carries more than a narrow one. Velocity is a factor; the quantity of débris carried varies greatly for small changes in the velocity along the bed. Bed velocity is affected by slope and also by depth, increasing with each factor; and depth is affected by discharge and also by slope. If there is diversity of velocity from place to place over the bed, more débris is carried than if the average velocity everywhere prevails, and the greater the diversity the greater the carrying power of the stream. Size of transported particles is a factor, a greater weight of fine débris being carried than of coarse. The density of débris is a factor, a low specific gravity being favorable. The shapes of particles affect traction, but the nature of this influence is not well understood. An important factor is found in form of channel, efficiency being affected by turns and curvature and also by the relation of depth to width. The friction between current and banks is a factor and therefore likewise the nature of the banks. So, too, is the viscosity of the water, a property varying with temperature and also with impurities, whether dissolved or suspended.

The enumeration might be extended, complexity might be further illustrated by pointing out the influence of conditions on one another, and the difficulty of measuring the detrital loads of streams might be dwelt upon, but enough has been said to warrant the statement that an adequate analysis with quantitative relations can not be achieved by the mere observation of streams in their natural condition. It is necessary to supplement such observation by experiments in which the conditions are definitely controlled.

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[1] Sir John Leslie's analysis is to be found in his Elements of natural philosophy, and in the edition of 1829 occurs at pages 426–427 of volume 1. David Stevenson mentions 1823, which probably indicates the first edition. William Hopkins gives a different analysis with practically the same result, and does not mention Leslie. The passage quoted occurs in Cambridge Philos. Soc. Trans., vol. 8, p. 233, 1844, and is probably from his earliest discussion of the subject. Wilfred Airy's later but evidently independent analysis appears in Inst. Civil Eng. Proc., vol. 82, pp. 25-26, 1885, with expansion by Henry Law on pp. 29–30.

[2] Deacon, G. F., Inst. Civil Eng. Proc., vol. 98, pp. 93–96, 1894.

[3] Fargue, L., Annales des ponts et chaussées, 1894.

[4] The equipment and work of the laboratory of river engineering of the Technical High School of Dresden are discussed in the Zeitschrift für Bauwesen, vol. 50, pp. 343–360, 1900, and vol. 55, pp. 664–680, 1905; the equipment of the laboratory of the Technical High School "Fredericiana" of Karlsruhe in the same journal, vol. 53, pp. 103–136, 1903, and vol. 60, pp. 313–328, 1910; and the equipment and work of the Laboratory for River Improvement and Naval Architecture, Berlin, in vol. 56, pp. 123–151, 323–324, 1906.

OUTLINE OF COURSE OF EXPERIMENTATION.

In the work of the Berkeley laboratory capacity for hydraulic traction was compared with discharge, with slope, depth, and width of current, and with fineness of débris; and minor attention was given to velocity and to curvature of channel. For the principal experiments a straight trough was used, the sides being vertical and parallel, the ends open, the bottom plane and horizontal. Through this a stream of water was run, the discharge being controlled and measured. Near the head of the trough sand was dropped into the water at a uniform rate, the sand grains being of approximately uniform size. At the beginning of an experiment the sand accumulated in the trough, being shaped by the current into a deposit with a gentle forward slope. The deposit gradually extended to the outfall end of the trough, and eventually accumulation ceased, the rate at which sand escaped at the outfall having become equal to the rate at which it was fed above. The slope was thus automatically adjusted and became just sufficient to enable the particular discharge to transport the particular quantity of the particular kind of sand. The slope was then measured. Measurement was made also of the depth of the current; and the mean velocity was computed from the discharge, width, and depth.

In a second experiment, with the same discharge, the sand was fed to the current at a different rate, and the resulting slope and depth were different. By a series of such experiments was developed a law of relation between the quantity of sand carried, or the load, and the slope necessary to carry it, this law pertaining to the particular discharge and the particular grade of sand. The same experiments showed also the relations of the velocity of the current to slope and load.

Another series of experiments, employing a greater or a less discharge, gave a parallel set of relations between slope, load, and velocity. By multiplying such series the relations between discharge and slope, discharge and load, and discharge and velocity were developed.

Then a third condition was varied, the width of channel; and finally the remaining condition under control, the size of the sand grains. Thus data were obtained for studying the quantitative relations between load, slope, discharge, width, and fineness, as well as the relations of depth and mean velocity to all others. In all, the range of conditions included six discharges, six widths of channel, and eight grades of sand and gravel, but not all the possible combinations of these were made. The actual number of combinations was 130, and under each of these were a series of measurements of load, slope, and depth. There were also limited series of experiments involving a greater number of discharges and a greater number of widths. The separate determinations of load and slope numbered nearly 1,200, and those of depth about 900.

SCOPE OF EXPERIMENTS.

Before proceeding to a fuller description of apparatus and experiments, let us consider to what extent the conditions of the laboratory were representative of the conditions which exist in the natural stream.

The sand used came from the beds of American and Sacramento rivers and was assumed to be representative of river sand in general. No attention was paid to the influence on traction of the form and density of grains. Each sample used was separated from the natural mixture by means of two sieves and was composed of grains which passed through a certain mesh and were arrested by a mesh slightly smaller. In the sand carried by a river near its bed the range of size is much wider. The limit of coarseness is found in those particles which the current is barely able to roll, the limit in fineness in those particles which the swirls of the current are not quite able to lift into suspension; and the limits vary from point to point of the channel bed. This difference in condition was not wholly ignored, but a short supplementary series of experiments was made with definite mixtures of sand of various sizes, as well as with a natural mixture.

The straight channel of the laboratory differs materially from the curved channels of nature. It gives comparatively uniform depths and velocities from side to side and from point to point in the direction of the flow, while in a curved channel the depths and velocities vary greatly both across and along the channel. This difference in condition also received some attention, a short series of experiments being made with crooked and curved channels.

The vertical sides of the troughs did not well represent the sloping banks of rivers, and no attempt was made to measure the qualification due to this difference. The cross section of the laboratory current was essentially a rectangle and the ability of the current to transport was found to be definitely related to the ratio between depth and width; but satisfactory connection was not made between this relation and the forms of cross section in rivers.

The thalweg of a river channel traverses an alternation of deeps and shoals, the deeps being characterized by a different system of velocities and by a different line of separation between the grades of débris carried severally by suspension and traction; but these contrasts were touched only in a qualitative way in the work of the laboratory.

Each experiment dealt with a slope in adjustment with a particular discharge and a particular grade of sand. In a natural stream the discharge is subject to variation, and its changes cause changes in the fineness of the material carried along the bottom. Load and the local slopes are ever in process of adjustment to the temporary conditions of discharge and fineness, but the adjustment is never complete. The general or average slope is adjusted to an indeterminate discharge which is neither the smallest nor the greatest. For this phase of disparity allowance is not easily made.

One of the conditions affecting velocities is friction on bed and sides of channel. Friction on the bed depends partly on the roughness of the bed and partly on the consumption of energy by traction. Its laws are the same in laboratory and in river. Friction on the sides depends on the character of the channel wall and must be materially greater on river banks than on the smooth sides of the experiment trough. The magnitude of the difference was not determined. Velocities are affected by the viscosity of the water, variations in this factor being caused by differences in temperature and by impurities in solution and in suspension. The transportation of small particles is affected by adhesion, a property varying with the mineral character of the particles and with the impurities of the water. These factors were ignored but are probably negligible in comparison with the factors tested. It may be mentioned, however, that the water of the laboratory was practically free from suspended material, whereas that of rivers is usually highly charged at the time of most active traction.

These comparisons serve to show that the investigation treats of a group of important factors of the general problem of stream traction but by no means comprehends all. Its results constitute only a contribution to the subject.

ACCESSORY STUDIES.

Incidental and accessory to the main inquiry were a number of minor inquiries. One pertained to the Pitot tube, a second to other methods of measuring velocity near the bottom, a third to the relation between the mean velocity of a loadless stream and the roughness of its channel bed, and a fourth to the mechanical process of hydraulic traction.

FLUME TRACTION.

In the experiments on flume traction the bed of the channel was not composed of loose débris but was the unyielding bottom of the trough. The same apparatus was used, with appropriate modifications. In each experiment slope of channel was predetermined, the trough being placed with definite inclination. The bed of the channel was given a definite quality of roughness or smoothness, and the material of the load was of a particular fineness or of a definite mixture of sizes. With a definite discharge flowing through the trough, débris was fed to the current at a definite rate, and the rate was gradually increased until clogging occurred. The rate of feed just before clogging was then recorded as the maximum load under the particular conditions. The series of experiments used two widths of channel, five textures of channel bed, six discharges, and seven grades of sand and gravel, besides mixtures. There were nearly 300 determinations of load.

APPARATUS AND MATERIAL.

EXPERIMENT TROUGHS.

The trough in which most of the experiments were made was of wood, 31.5 feet long, with an inside width of 1.96 feet. The height of the sides was 1.8 feet at the head and 1 foot at the end, the change being made by a series of steps. Its proportions and general relations are illustrated by figure 1. The surfaces were planed and painted. At the head, where water entered, the trough was connected with a tank by a flexible joint, a groove of the under side of the trough bottom resting on a semicylindric member of the tank, so as to constitute a hinge, and the walls of the trough being connected with the sides of the tank by a sheet of flexible rubber. Here also was a gate by which the flow from the tank could be stopped. Close to the opposite end of the trough was a cross trough 11 feet long, 2.5 feet wide, and 3 feet deep, rigidly attached to the experiment trough and extending below it. A rectangular opening in the bottom of the experiment trough, an opening having the width of that trough, permitted sand in transportation by the current to sink into the cross trough, which contained boxes to receive it. The width of the experiment trough was varied by means of a longitudinal partition which was given various positions. Its width at the end was also varied by means of two oblique partitions, the "outfall contractor," which merged with the sides a few feet from the end and could be adjusted as desired. For certain experiments false bottoms were added, with surfaces specially prepared as to roughness. These will be specifically described in connection with the corresponding observations. A second trough, having the same function as the one just described was 150 feet long but similar in width and style. Its sides were higher and it was not hinged at the head but remained horizontal. By temporary arrangements of partitions curved and crooked channels 1 foot wide were constructed within this trough. The shorter trough was installed in the basement of the Mining Building of the University of California; the longer one on the campus near by. (See Pl. I, frontispiece.) The longer trough was remodeled for the experiments on flume traction.

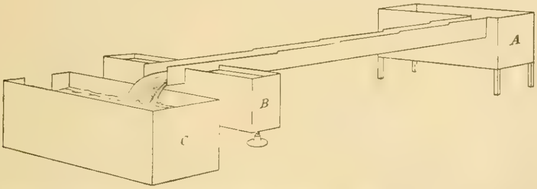


FIGURE 1.—Diagrammatic view of shorter experiment trough, showing relations to stilling tank (*A*), cross tank (*B*), and settling tank (*C*).

A third trough 14 feet long and 0.67 foot wide had its wooden sides replaced for a space of 3.5 feet, at midlength, by plate glass, so that observation could be made from the side. It was provided with a sliding diaphragm, to be described in another place.

A fourth trough, of iron, was used only in the experiments on flume traction and will be described in connection with those experiments.

A few experiments were made also in a trough carrying the waste water of the 150-foot trough. This had a width of 0.915 foot.

WATER SUPPLY.

The water was taken from the municipal mains of Berkeley. As it was not practicable to draw freely on this source, a moderate supply was made to serve for a long series of experiments, being stored in a sump and pumped up as required. By repeated use it acquired a certain amount of fine detritus in suspension, but the quantity was not sufficient to obstruct the view of the experiments—or rather, when it was found obstructive, a fresh supply of clear water was substituted.

THE WATER CIRCUIT.

Starting from the storage tank or sump, the water was lifted by a power pump to a high trough 13 feet above. In passing through this trough it was first quieted by baffles and then regulated as to surface level by means of a spillway about 13 feet wide, the overflow returning directly to the sump. At the end it sank slowly through a vertical shaft, or leg, whence it issued in a jet through an aperture regulated by a measuring gate. After spending its force against a water cushion it passed through a stilling tank and then through the experiment trough. From that it fell a short distance to a settling tank, and thence returned to the sump.

In figure 2 the circuit is shown diagrammatically but without accuracy as to the arrangement and relative sizes of the parts of the apparatus.

DISCHARGE.

For the control and determination of the discharges used in the experiments, a measuring gate was provided. Near the lower end of the vertical leg of the high trough the water issued through a rectangular opening in a brass plate. The gate, also of brass, sliding along the plate, controlled the size of the opening, its motion being given by rack and pinion and its position shown by a suitable scale. The head was about 6 feet and was determinate. The gate and its calibration are described in Appendix B (pp. 257–259).

The head was regulated by means of the spillway in the high trough, and the amount of overflow on the spillway was controlled by a gate valve in the supply pipe just above the pump. As a check on the control, the position of the water surface was shown in an inclined glass tube outside of the high trough. The index tube being nearly horizontal, its meniscus had a magnified motion and the condition of the head could be seen at a glance. (See fig. 88, p. 257.)

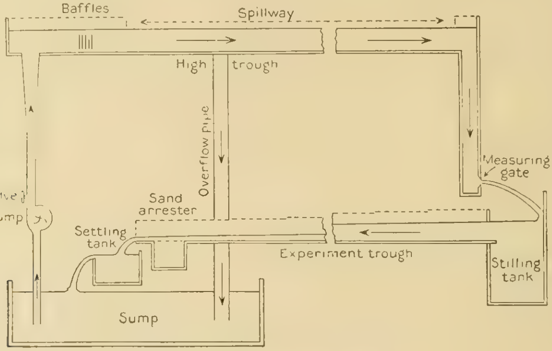


FIGURE 2.—Diagram of water circuit.

SAND FEED.

Above the experiment trough, and near its head, was a hopper-shaped box from which sand was delivered to the current in the trough. The box ended downward in an edge which stood transverse to the trough. Along this edge were a series of openings whose size was determined by a movable notched plate of brass. Water was supplied to the sand in the hopper, both at the top and near the bottom, the amount being regulated by valves. This water came from a small reservoir that was kept full by diverting part of the jet issuing from the measuring gate, and its use therefore added nothing to the measured discharge.

For some of the experiments débris was fed by hand, the quantity being regulated by means of a measuring box and a watch.

SAND ARRESTER.

The cross trough attached to the experiment trough and extending below it (see figs. 1 and 2) had along its bottom a track on which moved a platform car. This car carried two iron boxes to receive the sand. The boxes were rectangular and a little broader than the experiment trough. Openings protected by wire gauze permitted water to drain from them when they were lifted out.

SETTLING TANK.

The function of the settling tank was to catch sand which was carried past the cross trough. It was fitted with a system of partitions providing two alternative courses through which the stream could be turned, and with a hinged partition—the "deflector"—by which the diversion was made.

GAGE FOR DEPTH MEASUREMENT.

A frame resting on the experiment trough bore in vertical position a slender brass rod. This was raised and lowered by rack and pinion, and its relative height could be read on a scale. Depth of water was measured by reading the scale first with the rod end at the water surface and again with it at the débris surface.

LEVEL FOR SLOPE MEASUREMENT.

A surveyors' level stood a few yards from the trough, about equally distant from the ends, and was used, with a light rod, to measure relative heights for the determination of slopes of water surface and sand surface.

PITOT-DARCY GAGE.

A pressure-gaging apparatus of the Pitot-Darcy type, but of special pattern, was used to measure velocities of current. Its two apertures were directed severally upstream and downstream. Its external form was designed to give the least possible resistance to the current. The reading scale, with rubber-tube connection, had a fixed position, while the receiving member was moved from point to point. A fuller description is contained in Appendix A (pp. 251–256).

SAND AND GRAVEL.

The débris used in the experiments was obtained from three streams—Sacramento River 7 miles below the mouth of the American, American River 8 miles above its mouth, and Strawberry Creek in Berkeley. The débris from the creek was relatively coarse and was used only in the experiments on flume traction. The mean density of the river material was 2.69; that of the creek gravel 2.53. The forms of the grains of sand are shown in Plate II. To prepare the débris for use it was sorted into grades by a system of sieves, and in the laboratory records each grade was designated by the limiting sieve numbers. Thus the grains of the 40–50 grade passed through a sieve with 40 meshes to the inch and were caught by a sieve with 50 meshes to the inch. For the sake of brevity the grades are commonly indicated in this report by letters in parentheses—(A), (B), etc.—and the same notation is extended to mixtures of two or more sizes. Neither of these notations, however, is suited for the mathematical discussion of the laboratory data, and three others were devised. These are, first, the mean diameter of particles, designated by D; second, the reciprocal of the mean diameter, or the number of particles, side by side, in a row 1 foot long, designated by F; third, the number of particles necessary to occupy, without voids, the space of 1 cubic foot, designated by F_2. In the sense that the notation of D distinguishes by magnitudes, the notations of F and F_2 distinguish by minitudes. F is otherwise called *linear fineness*, and F_2 *bulk fineness*.

To determine the several constants for a grade of débris, a sample was weighed and its particles were counted. Then, N being the number of particles in the sample, W their weight, G their density, and W_o the weight of a cubic foot of water,

$$F_2 = \frac{NGW_o}{W}$$

Defining mean diameter as the diameter of a sphere having the volume of the average particle—

$$F = \sqrt[3]{\frac{\pi}{6}F_2}$$

$$D = \frac{1}{F} = \sqrt[3]{\frac{6F_2}{\pi}}$$

In the following table the grades of sand and gravel are characterized by the several notations.

TABLE 1.—*Grades of débris.*

Grade name.	Sieves used in separation (meshes to 1 inch	D, mean diameter of particles (foot).	F, number of particles to linear foot.	F_2, number of particles to cubic foot.	Range of D or F.	Range of F_2.
(A)...	50–60	0.00100	1.002	1,910,000,000	1.13	1.44
(B)...	40–50	.00123	812	1,023,000,000	1.17	1.60
(C)...	30–40	.00166	602	417,000,000	1.44	2.99
(D)...	20–30	.00258	388	111,500,000	1.56	3.80
(E)...	10–20	.00561	178	10,770,000	1.95	7.41
(F)...	6– 8	.0104	95.9	1,685,000	1.40	2.74
(G)...	4– 6	.0162	61.8	451,000	1.43	2.92
(H)...	3– 4	.0230	43.4	156,000	1.36	2.51
(I)...	1– 2	.0547	[18.3]	11,900	[2.00]	[8.00]
(J)...	½– 1	.110	[9.1]	1,440	[2.00]	[8.00]
(K)...	¼– ½	.200	[5.0]	239	[1.50]	[3.37]

The sixth column of the table contains an index of the range in diameter within each grade, and this is also the range in linear fineness. The index is the ratio between the diameters of the apertures of the two sieves by means of which the grade was separated. It would express accurately the ratio of the diameter of the largest particle to that of the smallest particle in the same grade if all the particles were spherical, or if all had precisely the same shape. But there are actual differences of form sufficient to modify materially the character of the separation. For the same mean diameter a prolate form will pass a sieve that will arrest a sphere, and an oblate form may be arrested where a sphere will pass. By reason of this qualifying condition, the actual range is somewhat greater than the tabulated estimate. The range for bulk fineness, given in the last column, is the cube of the range of linear fineness.

METHODS OF EXPERIMENTATION.

The methods here described are those used in the investigation of stream traction. Those used in studying flume traction are set forth in the chapter on that subject.

GENERAL PROCEDURE FOR A SINGLE EXPERIMENT.

The experiment trough stands horizontal. The width of channel has been fixed by the placing or the omission of the partition. The head gate is open. The openings in the hopper have been set to a particular size. The outfall contractor has been adjusted to a width previously found suitable for the conditions of the experiment. The two sand-catching boxes stand on the car, one of them being in position under the opening in the trough bottom.

The pump is started. The measuring gate is opened until its index reaches the point corresponding to the desired discharge. A valve associated with the pump is turned, if necessary, to adjust the water level in the high trough. When the flow in the experiment trough has become steady, or nearly steady, the sand feed is started by opening the valves which admit water to the hopper.

The "run" has now begun, and it is continued without change until the slope of the deposit constituting the channel bed has become stable. The car in the cross trough is now moved so as to bring the reserve sandbox into position, a stop watch is started, and the deflector in the settling tank is shifted. These changes begin the period of load measurement. During this period measurements are made of the depth of the current and, under certain conditions, of the slope of the water surface, and the character of the sand bed is recorded. The measuring period is terminated by again shifting the sand boxes and the deflector, and the watch is stopped. The head gate is now closed, sand feed and pump are stopped, and the discharge-measuring gate is closed. Next the slope of the channel bed is measured, and the sand caught during the period recorded by the watch is weighed.

DETAILS OF PROCEDURE.

In the following paragraphs some details and variants will be described, with comments on methods and apparatus. As the investigation had no precedents to follow, its methods were necessarily developed by a process of trial and and failure. Many defects of method were remedied as the work went on. A few that were recognized after much work had been done were tolerated to the end, because their correction would have made the body of results less homogeneous.

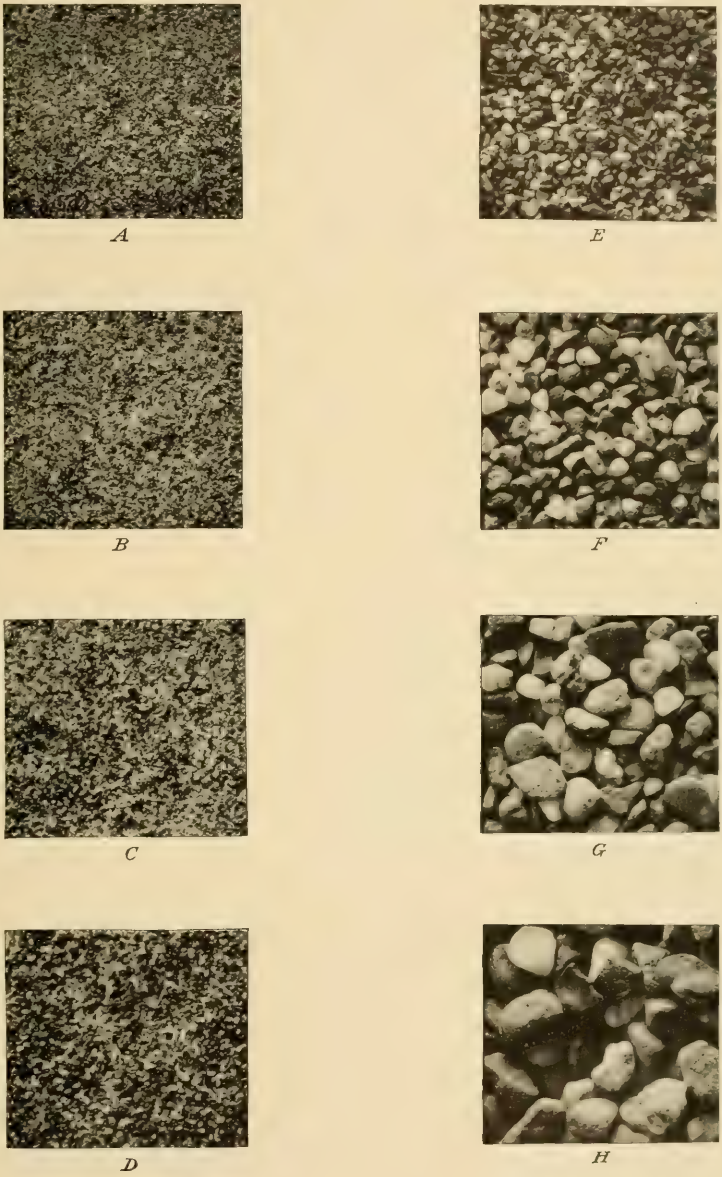
WIDTH OF CHANNEL.

The full width of the 31-foot trough and the 150-foot trough was 1.96 feet. By the use of partitions the channel was given widths approximately two-thirds, one-half, one-third, two-ninths, and one-ninth of a full width. The scale of width was, in feet, 0.23, 0.44, 0.66, 1.00, 1.32, 1.96. A few experiments employed also the widths 1.2, 1.4, 1.6, and 1.8 feet.

DISCHARGE.

As the discharge was determined by flow through an aperture of adjustable size, under an adjustable head, the precision of its measurement involved (1) the precision of setting the gate at the aperture, (2) the precision of calibrating the aperture for different positions of the gate, and (3) the precision of adjusting the head.

The rating (described in Appendix B) was effected by a volumetric method, believed to be adequate, the average probable error of its determinations being about 1 in 500.



A *E*

B *F*

C *G*

D *H*

DÉBRIS USED IN EXPERIMENTS

The gate was set by bringing an index mark opposite a graduation mark on a scale, the two marks being on brass plates in contact. The gate was controlled by rack and pinion, and considerable force was necessary to move it. The limit of error may have been 0.002 foot. The ordinary error is believed to have been less than 0.001 foot. An error of 0.001 foot in the setting would cause an error of 0.002 ft.^{3}/sec., or $\frac{1}{250}$ of the medium discharge.

The determination of head is subject to an accidental error and a systematic error. The accidental error pertains to the adjustment of water level in the high trough, by means of the valve at the pump, with observation of the tube index of water level. It was possible to give this adjustment a refinement comparable with that of the hook gage, but in practice that refinement was not attained, because a close watch was not kept on the index. It was found by experience that the fluctuations of level (occasioned by fluctuations of the electric current supplying power to the pump) were small, and they were usually neglected, a practical calibration of the valve at the pump being arranged so that it could receive the proper setting for each setting of the discharge measuring gate. The ordinary error of the adjustment of the head is estimated at 0.003 foot, which would occasion an error in the discharge of 1 in 4,000.

The remaining possibility of error is connected with the history of the apparatus. At the time of the calibration of the measuring gate the laboratory occupied temporary quarters. In its removal to permanent quarters there was a measurement and readjustment of the vertical distance constituting the head. Also, for the work with the long trough the measuring gate was transferred to a replica of the high trough, which may have differed in some particular affecting the constants. As the work of calibration was at no time repeated, there was no check on the errors which may have been thus introduced. In a general way, they are probably of the same order of magnitude as the errors of adjustment of water surface. It is believed that all other errors affecting discharge are small in comparison with that connected with the measuring gate.

The vertical width of the aperture by which discharge was regulated was 2 inches. The head, measured from the middle of the aperture, was 6.0 feet. The horizontal dimensions of the aperture, during experimental work, ranged from 0.1 inch to 6.0 inches, and the corresponding discharges are given in the following table:

Table 2.—*Gate readings and corresponding discharges.*

Gate opening (inches).	Discharge (ft.^{3}/sec.).	Gate opening (inches).	Discharge (ft.^{3}/sec.)
0.1	0.019	1.5	0.272
.2	.039	1.6	.290
.3	.058	1.7	.308
.4	.075	1.8	.327
.5	.093	1.9	.345
.6	.111	2.0	.363
.7	.128	2.5	.454
.8	.146	3.0	.545
.9	.164	3.5	.639
1.0	.182	4.0	.734
1.1	.200	4.5	.828
1.2	.218	5.0	.923
1.3	.237	5.5	1.021
1.4	.255	6.0	1.119

THE FEEDING OF SAND.

The fact that the hourglass has been used to measure time suggests that the flow of dry sand through an aperture may be uniform. Such a flow was not tested in the laboratory because the plan for experimentation required that sand should be used over and over, and it was not practicable to dry it. The hopper was a device intended to produce a uniform flow of wet sand. Moist sand will not flow through a small opening; but if enough water is present to more than fill the voids, adhesion is overcome and flow takes place, as in a quicksand. The freedom of the flow depends on the amount of water. It was found difficult to maintain a uniform condition in the hopper. Another difficulty arose from clogging of the openings, and this was occasioned by shreds of wood fiber and similar impurities in the sand. The second difficulty was largely obviated, after a time, by making the openings larger and fewer; but the hopper feeding was at best not sufficiently uniform to be used in measuring the load carried by the experimental stream.

For all experiments in which a large quantity of débris was carried, the material was fed to the current by hand and was measured in the feeding. A small box of known capacity was filled with the material and emptied into the current at regular intervals timed by a watch or clock. If the interval was long, the measured unit was dumped on a sloping table above the trough and gradually fed to the current by means of a scraper. Hand feeding had the defect of discontinuity, as well as irregularity in detail, but it had the advantage of measurement, and in certain experiments its measurement of load gave an important check on the measurement of débris delivered at the outfall end of the trough. With a perfect and stable adjustment of conditions the two should agree, and their disagreement served to show that the slope of the channel bed had not become perfectly adjusted, or else that its adjusted condition was subject to rhythmic oscillation.

In some of the later work the rate of feed was measured from time to time by intercepting the stream of sand falling from the hopper during a definite number of seconds and weighing the sample thus caught.

THE COLLECTION OF SAND.

In the original construction of the apparatus for arresting the sand the opening in the bottom of the trough was covered by a coarse wire screen, which lay flush with the trough bottom. This was intended to separate the current above from the still water below and prevent the formation of eddies, which might keep the sand from settling to the collecting box and might also check the current. It fulfilled its purpose and was altogether satisfactory for currents of moderate velocity, but with high velocities it interfered with the arrest of the sand, letting a considerable fraction pass on to the settling tank. It was accordingly removed, apparently without bad results. Eddies were formed, but the anticipated difficulties were not realized.

On the whole the apparatus for arresting sand was successful. It was only with the finer débris and at the highest velocities that the fraction of load escaping to the settling trough was too large to be neglected in the weighing.

DETERMINATION OF LOAD.

The sand collected, in sand box and settling tank, during the period recorded by the stop watch was weighed without drying, and the gross weight was afterward corrected by an allowance for the contained water. In order to determine the proper allowance a preliminary study had been made, and as a result of that study a definite procedure was adopted for bringing the wet sand to a particular "standard" condition. After the sand-collecting box had been lifted from the trough all water which would drain from it by gravity alone was allowed to escape. It was then removed to smaller boxes for weighing. These boxes were jarred by tapping, which caused the sand grains to readjust their contacts and settle together, excluding a part of the interstitial water, which appeared at the surface and was poured off. The sand was then weighed. It is of interest to note that in the condition thus adopted as a convenient standard sand occupies less space than when dry, moist, or supersaturated; its voids are at a minimum.

The period recorded by the stop watch was ordinarily about 10 minutes but was made less when the current was most heavily loaded, because of the limited capacity of the sand-collecting box, and was extended for the lightest loads. Its beginning was sharply defined by the shifting of the sand boxes, which could be made to coincide within a second with the starting of the watch. Its end was somewhat less definite, but the error in time is believed to be small in comparison with the whole period.

The load per second was computed by dividing the total load, namely, the corrected weight of sand, by the number of seconds in the stop-watch reading. Its error included (1) the error of timing, (2) the error of standardizing the sand and correcting for contained water, and (3) the error in weighing. There are no definite data bearing on its amount, and nothing better can be recorded than a general impression that the results are reliable within 2 per cent, that the precision is lower than that of the discharge measurement, and that the error in determination of load is notably less than the error, presently to be considered, in correlating load with slope.

When the rate of feed was regulated by the periodic contribution of a measureful of débris, the weighings of the unit, from time to time, showed inequalities from which precision could be estimated. A computation indicated the average probable error, for a run, as about 1 per cent. This depended chiefly on the standardization, and as that was less perfect for the débris as fed than for the débris as collected, the ordinary measurement of collected load is presumably affected by a smaller probable error.

DETERMINATION OF SLOPE.

The observations of slope were made with surveyors' level and rod. The rod, made for the purpose, without unnecessary length or weight, was graduated to hundredths of a foot and read by eye estimate to thousandths. It was held by an assistant while the observer and recorder stood at the telescope. The positions were determined by a graduation of the trough, which was marked at every foot. To measure the water slope, heights of the surface were taken at several points along the trough. To measure the sand slope, heights were taken at intervals of either 2 or 4 feet, the shorter interval being used with the shorter trough. The water slope could not be measured when the surface was rough. When the débris surface was rough, it was usually graded before measurement by scraping from crests into adjacent hollows.

The observed heights were plotted on section paper, with relatively large vertical scale, and a straight line was drawn through or among them. The line served the purpose of a preliminary determination of slope, and the plots were inspected for the detection of systematic errors. As a result of this inspection a portion of the profile was selected for the determination of slope, and from the observations on this portion the slope was computed by least-squares method.

CONTRACTOR.

As will be explained more fully in another connection, the slope measurements were affected (1) by systematic errors connected with the conditions under which the water entered and escaped from the trough, and (2) by accidental errors arising from rhythm. One of the measures used to diminish the systematic errors was the contraction of the current at the outfall end of the trough. The apparatus for this purpose consisted of two boards as wide as the depth of the trough and arranged as in figure 3. Their attachment to the sides was flexible, so that the degree of convergence and the width of aperture at the outfall could be modified at will. This apparatus will be called the outfall *contractor*. The theory and efficiency of the contractor will be considered in the discussion of the slope errors.

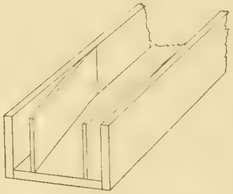


FIGURE 3.—The contractor.

MEASUREMENT OF DEPTH.

The depth of the current was measured at midwidth and near midlength of the trough. The determination was made by means of the gage already described (p. 21), during the period of time for which the load was measured. As the water surface was subject to rhythmic fluctuation, a series of observations of its position were made, and their mean was used. A series of observations of the position of the débris surface were sometimes made also, but usually only a single observation, and the reading obtained was subtracted from the mean of readings on the water surface. The observations of the débris surface were subject to an error which was regarded as more serious than that of the observations of water surface because, being essentially systematic, it could not be eliminated by repetition. The presence of the gage rod in the water modified the distribution of velocities, and this modification included an increase of the current's velocity a little below the end of the rod. As the bottom was approached by the rod, the current scoured a hollow in the bed immediately under it; and if the rod were lowered to actual contact, the reading would give an excessive estimate of depth. What was attempted was to lower the rod to a position as nearly as possible at the level of undisturbed parts of the bed surrounding the visible hollow. This was a matter of judgment, but not of confident judgment, because the actual bed was concealed by a cloud of saltatory débris particles. It is therefore recognized that the measurements of depth are uncertain.

Whenever the water profile as well as the débris profile was surveyed, an independent estimate of depth was obtained by subtracting one profile from the other. This mode of determination avoided the error incident to the gage work and was on the whole satisfactory, but unfortunately the number of experiments to which it could be applied was not large. During the greater part of the experimentation the importance of the water profile was not recognized, and this particular use of it was essentially an afterthought.

The values from profiles being assumed to have relatively small errors, both systematic and accidental, it is possible to measure by their aid the precision of the values from gage readings. Of 118 depths which were measured by both methods, the gage gave the greater value for 36, the lesser for 78; and the average for gage values was 0.0045±0.0007 foot less than the average for profile values. Independently of this apparent systematic error, the probable error of a single measurement with the gage was ±0.007 foot.

MEASUREMENT OF VELOCITY.

The mean velocity of the current is computed by dividing the discharge by the area of the cross section, or the product of width and depth. Its precision depends on those of the determinations of discharge, width, and depth; and as the precision for discharge and width is relatively very high, the precision of mean velocity may be regarded as identical with that of depth.

The attempts to measure velocity close to the channel bed were not successful. This is much regretted, because it is believed that bed velocity is a prime factor in traction and that slope and discharge exert their influence chiefly through bed velocity. The mode of measurement to which most attention was given was that by the Pitot-Darcy gage, and special forms of that instrument were constructed for the purpose. The difficulty which seemed insuperable was essentially the same as that encountered in the measurement of depth. As the instrument approached the current-molded bed of débris, the bed retreated, with the formation of a hollow. In the presence of the instrument the normal velocity at the bed did not exist. Inseparable from this difficulty is a property of the instrument. When it is held close to the bottom or side of a channel its constant is not the same as in the free current. The system of flow lines and velocities with which the stream passes the obstructing object determines the instrument's constant, and when that system is modified by a neighboring object the constant changes. The nature of these difficulties is such that it was not thought worth while to experiment with other gages and meters which limit the freedom of the current.

Other devices tried were of one type. Small objects, such as currants or beans, only slightly denser than water, were placed in the current and watched. The lighter ones would not remain near the bottom. The heavier ones were visibly retarded when they touched the bed and were also retarded when close to the bottom by the cloud of saltatory sand, which has a slower average velocity than the water it suffuses.

MODES OF TRANSPORTATION.

MOVEMENT OF INDIVIDUAL PARTICLES.

ROLLING.

In stream traction sliding is a negligible factor. The roughness of the bed causes particles that retain contact to roll. When, as in most of the experiments, the grains are of nearly uniform size, each moving grain has to surmount obstacles with diameter like its own, and when it reaches the summit of an obstacle it usually possesses a velocity which causes it to leap. So rolling is chiefly the mere prelude to saltation. With mixed débris the same is true for the finer grains, but the coarser may roll continuously over a surface composed of the finer, and the coarsest of all, those close to the limit of competence, move solely by rolling.

The large particle, as it rolls over the bed of smaller particles, indents the bed, and its contact involves friction. The energy thus expended comes from the motion of the water, and its communication depends on differential motion between water and particle. Except under special conditions, to be mentioned later, the load travels less rapidly than the carrier, and it is also true that in a load of mixed débris the finer parts outstrip the coarser.

SALTATION.

In stream traction the dominant mode of particle movement is saltation. Because saltation grades into suspension it has often been explained in the same manner, by appeal to upward movement of filaments of current, but the recent studies have led me to entertain a different view. Before this view is presented an account will be given of certain observations which were made with the use of the trough having glass sides.

Through the trough was passed a current transporting sand of uniform grade, and the conditions were such that the sand bed and water surface were smooth. In the same water floated a few fine particles and thin flakes of mica, illustrating suspension, but there was no intergradation of the two processes. Viewed from the side, the saltation was seen to occupy at the bottom of the current a space with a definite upper limit, parallel to the sand bed. Within this space—the zone of saltation—the distribution of flying grains was systematic, the cloud being dense below and thin above, but not perceptibly varying from point to point along the bed. Viewed from above, the surface of the cloud seemed uniform and level, and it all appeared to be moving in the same direction. There was no suggestion of swirls in the current.

When, in looking from the side, attention was directed to the base of the zone, it was easy to watch grains that traveled half by rolling and half by skipping, and these moved quite slowly; but higher in the zone the motions were so rapid and diverse that all was a blur. To resolve this blur a sliding diaphragm was arranged. This consisted of a short board with a hole in it. The board hung outside the wall of the trough, being supported by a cleat above in such manner that it could be slid along the trough. (See fig. 4.) The hole, about 2 inches square, gave a restricted view of the saltation zone. By sliding the board in the direction of the current and keeping the eyes opposite, a traveling field of view was obtained. Manifestly if the field traveled at the same rate as the current, any object moving with the current would appear at rest to the observer, because there would be no relative motion of observer and object; and if objects in the water were moving (horizontally) at different rates, those coinciding in rate with the field would be seen as if at rest, while the others would be seen as moving.

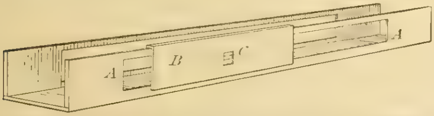


FIGURE 4.—Diagrammatic view of part of experiment trough with glass panels (*A*) and sliding screen (*B*). *C*, Hole in screen.

When the field was moved slowly the rolling grains ceased to be distinct but were replaced in distinctness by grains that seemed to bob up and down. These vibrated through a space of two or three diameters, as if repeatedly striking the bed and rebounding. In interpreting this appearance, allowance must be made for the fact that the grains were distinctly seen because they were moving horizontally about as fast as the diaphragm. Their paths were really low-arching curves, and only the vertical factor remained when the horizontal was abstracted. It is probable also that the appearance of rebounding was largely illusory, most of the grains either stopping at the end of the leap, or else leaping next time with a different velocity.

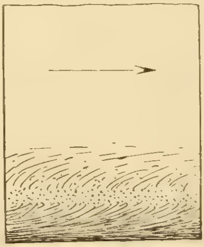


FIGURE 5.—Appearance of the zone of saltation, as viewed from the side with a moving field.

When the field was moved somewhat faster, the bobbing grains disappeared and there came into distinct vision a set of grains quite free from the bed and occupying a belt within the saltation zone. All the zone above and below them was blurred. In the middle of the belt vertical motion was to be discerned but was less conspicuous than in the lower zone. Where distinctness graded into blurring, lines of motion could be seen which were oblique and curved, the lines above the belt curving forward and those below backward, as shown in figure 5.

With progressively faster motion of the field the belt of distinct vision rose higher, until the top of the zone was reached, when all the lower part was blurred.

The systematic gradation of velocity and other features from the bed upward and the sensible uniformity of process over the whole width of channel are not consistent with the idea that the saltation zone is invaded by eddies of large dimensions, such as would be competent to sustain the grains by the upward components of their motions. If there were large ascending and descending strands of current the visible surface of the zone would be locally raised and depressed by them. We must, indeed, assume that the flow is turbulent, in the technical sense, because parallel or laminar flow is impossible with velocities competent for traction, but the eddies may be assumed to be of small dimensions in relation to the depth of the zone, and the lines of flow with which saltation is concerned may be assumed to be approximately parallel to the general direction of the current.

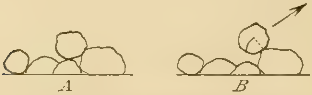


FIGURE 6.—The beginning of a leap, in saltation.

The explanation I would substitute for that of the uplift of grains by rising strands is that each grain is projected from the bed with an initial velocity which gives it a trajectory analogous to that of a cannon ball. The following fuller statement, though given with little qualification, should be understood as largely hypothetic.

In figure 6 the current is supposed to move from left to right above the grains of débris shown in outline. A grain which in *A* is at rest appears in *B* in an advanced position, having been rolled upward and forward about an undisturbed grain which lies in its way. (The moving grain is doubtless more likely to roll against two other grains than a single one, but the principle is the same.) In moving to its new position the center of gravity of the grain describes a curve convex upward. The grain continuously gains in velocity, and the acceleration also increases as the direction of motion comes to make a smaller angle with the direction of the current. At each instant the accelerative force due to the current and that of gravity are combined and have a resultant direction; and the combined or resultant accelerative force may be resolved into two parts, one of which coincides in direction with the motion of the center of gravity and the other with the line joining the center of gravity and the point of contact. The last-mentioned component presses the moving grain against the stationary grain. Opposed to it is the centrifugal force arising from the curvature of the grain's path; and the point is finally reached where the centrifugal force dominates and the grain is free. Under the ordinary conditions of saltation this point is not the crest of the obstruction, but is on the upstream side, so that the grain's direction of motion at the instant of separation is obliquely upward. Thus the free grain is initially moving upward as well as forward, and it has almost literally made a leap from the bed.

If the grain were at that instant released from all influences but gravity, its path before returning to the bed would be the arc of a quadric parabola with vertical axis. The actual deviation of its trajectory from the parabolic form is analogous to that observed in gunnery, for it arises from the resistance of a fluid; but the laws of resistance are not the same for air and water, and the frictional acceleration in one case is negative while in the other it is mainly positive. The trajectory in gunnery is shorter than the ideal parabolic arc; in saltation it is longer.

Figure 8 gives diagrammatically the trajectory of a saltatory grain. In figure 7 *AB* is a portion of the same trajectory. Let the space *AC* represent the instantaneous velocity of the grain, and let the line *AD* represent in direction and length the velocity of the water about the grain. Then, *C* and *D* being connected by a line, *CD* represents in direction and magnitude the relative velocity of water and grain, or the velocity of the water as referred to the grain. By reason of the mutual resistance of water and grain, this relative motion accelerates the grain, the acceleration being a function of the differential velocity, the size of the grain, and other conditions. On the line *CD*, showing the direction of the acceleration, let the space *CE* represent its amount. Then from *E* draw the vertical *FF*, represent-

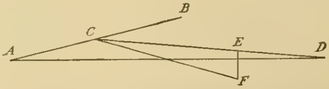


FIGURE 7.—Diagram of accelerations affecting a saltatory grain.

ing, to the same scale, the acceleration of the grain by gravity. Connect *C* and *F;* the line *CF* represents in magnitude and direction the resultant acceleration of the grain. These relations are independent of the particular directions of motion of the grain and the water. Let us now introduce the assumptions, believed to be practically true for the laboratory conditions, that the water in the region of saltation moves parallel to the bed and that its velocity increases notably with distance from the bed. In the ascending part of its path the grain encounters filaments of the current with higher and higher velocity. This tends to increase the relative velocity, but the grain is at the same time gaining in horizontal velocity and the gain tends to diminish the relative velocity. Unless the leap is short in relation to the size of the grain, the second of these tendencies is the greater, and at the highest point of its path the grain is moving nearly as fast as the water. In the descending part of its path it encounters slower moving filaments of current, and at some point (*H*, fig. 8) its horizontal motion may equal that of the adjacent water. Then beyond *H* it passes through filaments moving still more slowly, and its acceleration from the reaction of the current becomes negative. The acceleration due to gravity is of course uniform and downward, and its combination with that due to the current yields a system of directions and magnitudes of the type indicated in figure 8 by short arrows. In the shorter and lower trajectories it is probable that the critical point *H* is not reached.

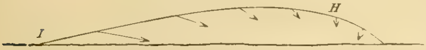


FIGURE 8.—Theoretic trajectory of a saltatory particle, the initial point being at *I*. Arrows indicate acceleration.

If the position of the grain before leaping (fig. 6) is such that only a relatively short roll suffices to free it, then its initial velocity is small and the angle of ascent at which it is freed is low. It has a short, flat trajectory, and its velocity at the highest point is moderate. If the original roll is longer there is time to acquire speed before the leap; the initial velocity is large and the angle of ascent is relatively high. It has a long and high trajectory and when at the crest has been accelerated to high velocity. If a grain at the end of a leap touches the bed at a favorable point it may leap again without coming to rest, and the impetus of the first flight will thus enhance the initial velocity of the second.

In the observations with the moving field the grains seen most distinctly were those which moved horizontally with the field and at the same time had little vertical motion. So each belt of distinctness contained grains at the tops of their trajectories and was practically made up of such grains. The grains producing the curved lines in figure 3 were ascending or descending obliquely, and their horizontal components of motion coincided with the motion of the field for an instant only.

In general the observations seem to show that the summit velocities of the leaping grains increase systematically with the height of the leap, and this generalization is in perfect accord with the hypothesis that the paths of grains are determined primarily by initial impulse.

Under the hypothesis the series of velocities observed by aid of the moving field are not velocities of current, for the initial velocities of grains, being caused by the current, require that the water outspeed all the grains at the bottom of the zone of saltation. At the top of the zone there must be at least a slight advantage with the current, provided the water velocities increase upward. That the water velocities do increase upward can hardly be doubted, for in sweeping along the sand the stream expends energy, and as its energy subsists in velocity, the expenditure involves retardation. Moreover, the grains of sand are at the same time most numerous and slowest near the bottom of the zone, so that their effect is there greatest.

In this connection it is to be observed that the width of the belt of distinct vision in the moving field (fig. 5) is greater for the upper part of the zone of saltation than for the lower. As distinct vision is limited to a certain (undetermined) range in horizontal velocities, this fact implies that the increase in horizontal speed of sand grains with distance from the bed is less rapid in the upper part of the zone than in the lower.

The preceding discussion is subject to two qualifications, the first of which is connected with the retardation of the current at the side of the trough. By reason of that retardation the zone of saltation is shallower near the side and does not include the longer and higher leaps. Figure 9 gives an ideal conception of the cross section of the zone and the distribution of flying grains within it. Observation from the side penetrates but a short distance into the cloud, the distance being least where the cloud is most dense. The practical limit of visual penetration may be assumed to take some such form as the line *AB*. Thus the tract actually studied in the work with the moving field was somewhat superficial and was not in strictness a vertical section of the zone.

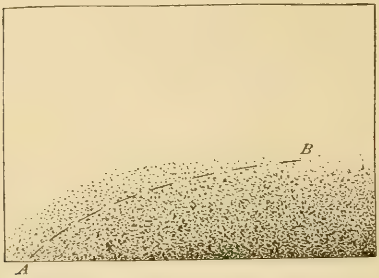


FIGURE 9.—Ideal transverse section of zone of saltation at side of experiment trough.

The second qualification is connected with turbulence. In steady flow the motion at each point of a stream is constant in velocity and direction. When the general velocity exceeds a certain minimum, which for the streams we have to consider is very small, the flow is not steady, but involves eddies or vortices, which as a rule move onward with the current. In consequence of these eddies the course of each particle of water is sinuous, and the sinuous courses interweave. The flow is then said to be turbulent. Usually there are both large and small eddies, the minute ones being multitudinous. As the axes of whirling movements have all attitudes, the directions of motion, as a rule, have upward or downward components, and the suspension of particles of débris is due to the upward components. Particles so small that they can not come to rest on the bottom are thereby lifted and relifted and kept in the body of the water. Under the conditions arranged for the study of saltation there appeared to be no large eddies, but the zone was unquestionably pervaded by small ones, excited by the roughness of the bed and by the differential motions of water and leaping grains. With increasing strength of current the texture of turbulence would enlarge and saltation pass into suspension. With a diversified débris, instead of the uniform material actually used, there would be phases of action in which the paths of small grains were made sinuous by turbulence, while those of larger grains remained simple in form. The trajectory of saltation, as described, may therefore be regarded as a simple type of path which combines in all proportions with the sinuous type of path characterizing suspension.

Through the entire zone of saltation motion is being communicated to particles of the load by the water, and there is a corresponding loss of motion by the water. That loss reduces all the stream's velocities but makes the greatest reduction in the lower part of the zone of saltation. The loss of velocity in the lower strands reduces their power to cause particles to leap. The greater the load the greater this reduction, and thus the quantity of load is automatically regulated.

COLLECTIVE MOVEMENT.

In the experiment used to illustrate saltation the collective movement of the sand was uniform, the conditions of the experiment having been adjusted to that end. But it is equally possible so to adjust them as to make the collective movement rhythmic. Uniformity is in fact an intermediate phase between two rhythmic phases, which are of contrasted types. These phases will be described.

In another experiment a bed of sand was first prepared with the surface level and smooth. Over this a deep stream of water was run with a current so gentle that the bed was not disturbed. The strength of current was gradually increased until a few grains of sand began to move and then was kept steady. Soon it was seen that the feeble traction did not affect the whole bed, but only certain tracts, and after a time a regular pattern developed and the bed exhibited a system of waves and hollows. As the waves grew the amount of transportation increased, showing that, under the given conditions, the undulating surface was better adapted to traction than the plane. With such waves and hollows are associated a special mode of transportation, which is illustrated in figure 10. A current reaching the bed at *A* follows the rising slope and crest of the wave to *C* and then shoots free, to reach the bed again at *D*. The space overleaped between *C* and *D* is occupied by one or more slow-moving eddies. From *A* to *C* there is traction, the material being derived from the slope between *A* and *B*. At *C* the débris, being abandoned by the current, is dumped, and it slides by gravity down the slope *CE*. So the upstream face of the wave is eroded and the downstream face built out, with the result that the wave, as a surface form, travels downstream. As this is precisely what takes place when a sand hill travels under the influence of the wind, the name of the eolian hill has been borrowed, and the waves are called *dunes*.[1] In one of the narrower troughs of the laboratory the dunes formed a single line. In a wider trough their arrangement sometimes suggested a double line, the crests of one being opposite the hollows of the other, but their arrangement continually changed. On the bed of a broad, shallow stream they are apt to have a subregular imbricated pattern.[2] In a deep stream a single dune may be nearly as broad as the channel. In the laboratory the forms were inconstant, but the type was about as broad as long, with the front edge convex downstream. In natural streams the dunes show great variety in outline, some being described as longest in the direction of the current and others as greatly extended in the transverse direction. They vary in size with the size of the stream, but especially with the depth, and are transformed and remodeled with increase and reduction of discharge. The horizontal dimensions of most laboratory examples may be conveniently described in inches, but river examples may require scores or hundreds of feet.[3] The maximum height in the laboratory was probably 2 inches; for those in Sacramento River 2 feet has been reported, and for those in the Mississippi 22 feet.

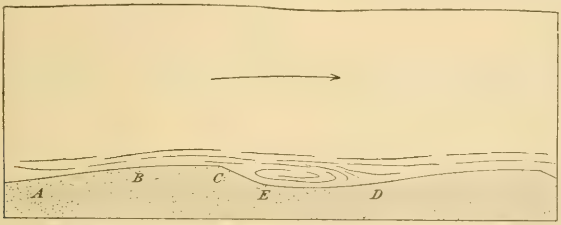


FIGURE 10.—Longitudinal section illustrating the dune mode of traction.

In each series of laboratory experiments to determine the relation of load to slope the initial run was made with a small load, while for the succeeding runs the load was progressively increased. Enlargement of the load caused increase of slope and velocity, with decrease of depth, and these changes were accompanied by changes in the mode of transportation. In the earlier runs dunes were formed, and these marched slowly down the trough. Then, somewhat abruptly, the dunes ceased to appear, and for a number of runs the channel bed was without waves and approximately plane, although somewhat ruffled in the run immediately following the disappearance of dunes. Finally a third stage was reached in which the bed was characterized by waves of another type. These are called *antidunes*, because they are contrasted with dunes in their direction of movement; they travel against the current instead of with it. Their downstream slopes are eroded and their upstream slopes receive deposit. They travel much faster than the dunes, and their profiles are more symmetric. The water surface, which shows only slight undulation in connection with dunes, follows the profiles of antidunes closely and shares their transformations.[1] (See fig. 11.) Usually each antidune occupied the full width of the experiment trough; and in natural streams, so far as I have observed, they either reach from side to side of the channel or else form well-defined rows in the direction of the current. Not only is a row of antidunes a rhythm in itself, but it goes through a rhythmic fluctuation in activity, either oscillating about a mean condition or else developing paroxysmally on a plane stream bed and then slowly declining. Paroxysmal increase starts at the downstream end of a row and travels upstream, gaining in force for a time, and the climax is accompanied by a combing of wave crests. Where the débris is very coarse, as on the outwash plains of glaciers, a din of clashing bowlders is added to the roar of the water.[2]

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[1] This is the name chiefly used by Swiss investigators (see De Candolle, Arch. sci. phys. et nat., vol. 9, p. 242, 1883, and Forel, idem, vol. 10, p. 43, 1884), and many observers compare the subaqueous feature to the eolian; but the specific title commonly used in the United States and Great Britain is *sand wave*, and some French engineers employ *grève*. In the present paper, dune is preferred to sand wave because there is occasion to distinguish two species of débris waves.

[2] The imbricated pattern is frequently seen beneath tidal waters, where ripple marks due to the reaction of wind waves are transformed into dunes when the tidal current sweeps across them. It is then usually to be ascribed to a difference in direction of the two actions. An elaborate account of its development in rivers is given by H. Blasius, who has recently investigated the whole subject of the rhythmic features of river beds. See Zeitschr. Bauwesen, vol. 60, pp. 465–472, 1910.

[3] Arthur Hider, who studied dunes in the lower Mississippi, reported a maximum length, crest to crest, of 750 feet, a maximum height of 22 feet, and a maximum progression of 81 feet in a day. See Mississippi River Comm. Rept., 1882, pp. 83–88 (=Chief Eng. U. S. A., Rept., 1883, pp. 2194–2199).

Of the phases of process in the laboratory Mr. Murphy writes:

> Their [the dunes'] form is continually changing as they move forward; they divide and again unite, the parts traveling at different rates, and new ones form on top of the older ones. The grains roll up the gentle slope, fall over the crest, are covered by other grains, and rest until the dune again passes over them and they are again uncovered. Thus the time during which they are in motion is small compared to the time during which they rest. As the velocity of the current increases, the rate of feeding being correspondingly increased, the size of the dunes and their rate of movement increase. Thus we find that when the discharge is 0.363 ft.^{3}/sec., load 11 gm./sec., and slope 0.32 per cent, the dunes are 7 to 9 inches long and one-half inch high and move at the rate of 0.56 foot a minute, but when the discharge is 0.734 ft.^{3}/sec. and the load 30 gm./sec., the dunes are 13 to 15 inches long, three-fourths of an inch high and move at the rate of 1.5 feet a minute. As the velocity of the current increases some of the grains leap as well as roll, and some, instead of dropping over the crest of a dune and resting, leap to the next dune. The dune grows less distinct in form and finally at a critical velocity it disappears, dune motion ceases, and the sand surface becomes comparatively even. This condition of even surface flow continues as the slope increases until at another critical velocity antidune movement begins. A profile of the sand surface for this kind of motion is shown in figure 11. For this experiment the trough width is 1.32 feet, discharge 0.734 ft.^{3}/sec., load 213 gm./sec. and the sand slope 1.23 per cent. These sand waves are from 2 to 3 feet in length from crest to crest, they extend the width of the trough, and some of them are 0.5 foot in height from crest to trough of the wave. They travel slowly upstream, some of the sand being scoured from the downstream face in the vicinity of *Y* (fig. 11) and deposited on the upstream face at *X*. Some of these waves remain for two minutes or longer, but most of them not longer than one minute. A whitecap forms on the surface of the water when the larger waves disappear. Sometimes two or more will disappear at once and leave the surface without waves for a distance of 10 feet or more. Only a portion of the sand transported takes part in the formation of these sand waves. The velocity in a wave trough is greater than near the crest. The sand grains flow nearly parallel to the bed as they pass through the trough, but at the crest they have an up and down motion as well as a forward motion. On the crest of the larger waves their forward motion is small compared with their vertical motion. * * *
>
> There is a sand movement by rotation or whirls that aids transportation. These whirls have been observed during dune motion only for smaller sizes of sand. They are of short duration, lasting usually less than one minute, but in this time one of these may scour a hole 1 to 3 inches deep and 4 to 10 inches in length. They usually start near the side of the trough, the axis inclining downstream and toward the center, making an angle of 30° to 60° with the side and a small angle at the bottom. These whirls are 3 to 5 inches in diameter and the sand grains are thrown violently up as well as downstream by them. This movement aids transportation by its lifting action, some of the grains being carried in suspension for a short distance by it.
>
> The change in the appearance of a loaded stream as the load is increased, the discharge remaining constant, is very striking. For no load the water surface is even and smooth. As fine sand is fed into the water at a slow rate, small sand dunes will form on the bottom and many little waves will form on the surface. As the rate of feeding is increased, the slope and velocity increasing, these waves become larger and fewer and have the shape of an inverted canoe. These canoes are side by side, the number depending on the trough width and size of waves. When the width was 1.0 foot two sets formed side by side; when

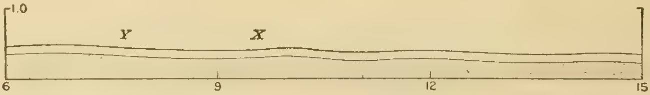

FIGURE 11.—Longitudinal section illustrating the antidune mode of traction. The numbers show distance in feet from the head of the experiment trough.

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[1] Antidunes, though less common than dunes, are by no means rare under natural conditions. They are described by Vaughan Cornish (Geog. Jour. (London), vol. 13, p. 624, 1899; Scottish Geog. Mag., vol. 17, pp. 1-2, 1901), and are mentioned by John S. Owens (Geog. Jour., vol. 31, p. 424, 1908).

[2] The sequence of bed characters—dune, smooth, antidune—was observed by John S. Owens in studies with natural currents in 1907, and the characters were correlated with velocities. With depths of 3 to 6 inches and a bed of sand, he noted sand ripples [dunes] when the velocities, measured by floats, were from 0.85 to 2.5 ft./sec., and the appearance of antidunes at a velocity of about 3 ft./sec. (Geog. Jour. (London), vol. 31, pp. 416, 424, 1908). Sainjon and Partiot, studying the movement of débris in the Loire, had previously observed that whereas with low velocities the entire bottom load was transported through the progress of dunes, with higher velocities the débris was swept along from crest to crest and the dunes were reduced in height (Annales des ponts et chaussées, 5th ser., vol. 1, pp. 270-272, 1871).

the width was 1.32 feet three sets formed. As the critical velocity at which dune motion ceases is approached these waves begin to disappear, and when this velocity is reached the water surface is waveless. This waveless condition continues as the rate of feed increases until sand motion in antidunes begins, when large waves, the width of the trough and corresponding in length to the sand waves beneath them, are formed as illustrated in figure 11.

In order to show the magnitude of these surface waves, wave traces have been drawn. Some of these are given in figure 12. A sheet of galvanized iron 4 feet long and 1 foot high was divided into inch squares by lines. This plate was moistened and covered with fine dust. It was held vertical at a given place over the experiment trough and on signal was dropped into the trough and taken out again as quickly as possible. The dust was removed from that part of the plate in the water, leaving a well-defined outline of the wave. This wave trace was quickly sketched on paper by means of the lines marking the squares. Trace *A*, figure 12, is for zero feed; *B* is for a very small feed; *C* is for a larger feed, the surface being covered with the canoe-shaped waves; *D* shows one of the larger waves associated with antidunes.

The slopes at which the phases of traction change are lower for large streams than for small, and lower for fine débris than for coarse. The phase with smooth bed—which may conveniently be called the smooth phase—covers a greater range of conditions with mixed débris than with assorted.

The processes associated with dunes and antidunes were briefly studied in the glazed trough and with the moving field. Transportation by saltation follows the entire profile of the antidunes but traverses the dunes only from *A* to *C* of figure 10. The velocity of saltatory grains is greatest where erosion takes place, namely, along the upstream slopes of dunes and the downstream slopes of antidunes, and it may reasonably be inferred that the water velocities are greatest in those places. The eye detected no difference in water depth over the two slopes of the antidune, and if the depth is the same so also is the mean velocity; but the ratio of bed velocity to mean velocity is known to vary with conditions.

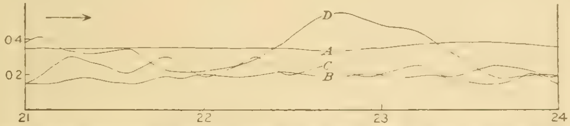

FIGURE 12.—Profiles of water surface, automatically recorded, showing undulations associated with the antidune mode of traction. Numbers show distance, in feet, from the head of experiment trough.

The cause of the changes in process has not been adequately investigated, but a few suggestions may be made. To assist in a search for controlling conditions, the factors connected with the two critical points—the change from dune phase to smooth and the change from smooth to antidune—were tabulated from the experiments with sand of a single grade (C); the positions of the critical points being estimated by Mr. Murphy at a time when the details of the experiments were freshly in mind. In Table 3 *w* is the width of trough, in feet; *Q* the discharge, in cubic feet per second; *S* the per cent of slope; *d* the depth of water in feet; V_m the mean velocity, in feet per second; *L* the load, in grams per second; and L_1 the load per unit width. The data in this table are taken from a preliminary reduction of the observations and are less accurate than the results of the final adjustment, which appear in Table 12 (p. 75). They suffice, however, for the present purpose.

TABLE 3.—*Data connected with changes in mode of transportation.*

w	Q	First critical point.					Second critical point.				
		S	d	V_m	L	L_1	S	d	V_m	L	L_1
0.66	0.093	1.00	0.076	1.86	13	20	1.86	0.058	2.44	44	67
.66	.182	.93	.115	2.41	28	46	1.72	.092	3.01	88	134
.66	.363	.82	.190	2.91	48	73	1.51	.165	3.37	145	221
.66	.545	.74	.272	3.05	70	106	1.34	.209	3.97	184	281
1.00	.182	1.15	.082	1.76	41	41	2.02	.056	3.25	111	111
1.00	.363	.89	.134	2.71	70	70	1.70	.109	3.33	201	201
1.00	.545	.81	.180	3.03	95	95	1.51	.142	3.75	244	244
1.00	.734	.73	.227	3.24	113	113	1.34	.194	3.78	301	301
1.32	.182	1.20	.068	2.03	33	25	2.15	.051	2.70	121	92
1.32	.363	1.00	.107	2.57	76	57	1.76	.099	2.77	210	159
1.32	.545	.87	.145	2.84	106	80	1.53	.111	3.71	251	190
1.32	.734	.75	.178	3.13	140	106	1.33	.149	3.73	293	222
1.96	.363	1.04	.081	2.29	67	34	1.91	.062	2.99	219	112
1.96	.734	.84	.133	2.82	138	71	1.48	.108	3.47	354	181
1.96	1.119	.74	.182	3.14	191	98	1.22	.150	3.81	418	213

The factors were then plotted in various combinations on logarithmic section paper, and certain approximate numerical relations were thus discovered. The first critical point is reached when $d=0.016\ V_m^{2\cdot3}$, or when $d=0.0045\ L_1^{0\cdot85}$. The second critical point is reached when $d=0.004\ V_m^{3\cdot3}$, or when $d=0.0003\ L_1^{1\cdot15}$. The coefficients and exponents are not well defined by the data, but the general indications are (1) that each change in phase occurs when the depth of water bears a certain numerical relation to a power of the mean velocity near the cube, and (2) that the changes occur when the depth bears a certain numerical relation to the amount of load carried in each unit of width of current.

At the bottom the stream is limited and restricted by the bed of débris; at the top by the water surface. To the space between these bounds, a space measured by the depth, the eddies or convolutions of the current are confined. Within the range of conditions covered by the experiments the normal mode of flow involves sinuosity of the filaments of current, and the tendency toward diversity of internal movement is strong in proportion as the velocity is high. A particular relation between depth and velocity corresponds to a sort of equilibrium between the factors of turbulence and restraint, in accordance with which the sinuosity of the lines of flow is reduced to a minimum and the water surface and channel bed are approximately plane. This gives the smooth phase of traction. When the depth is increased without increase of velocity, the reduction of restraint permits the development of internal diversity, and this carries with it diversity of the plastic bed, giving the dune phase of traction. When the velocity is increased without increase of depth, the restraint is overpowered, and a diversified but systematic arrangement of flow lines develops, which carries with it systematic diversity of both water surface and channel bed and gives the antidune phase.

There will be occasion to speak of these relations in another connection in Chapter XIV.

It may be noted, as a possible contribution toward an explanatory analysis, that gravity opposes the current on the upstream side of the antidune (fig. 11) and assists the current on the downstream side. It is where gravity accelerates that load is increased by erosion, and where gravity retards that load is reduced by deposition. In the case of the dune, however, erosion occurs where gravity is a retarding force. But here the descending current, which is accelerated by gravity and which is observed to have gained speed, is free from the bed and bears no load (fig. 10). In order to transport when it resumes contact with the bed it must take débris from the bed, and by so taking it erodes.

UNITS.

The system of units to which the laboratory data have been reduced and which will be employed in their discussion is hybrid in that it includes the foot and the gram. The foot is made the fundamental unit for length, area, and volume because it is the unit employed generally by English-speaking engineers. The gram is made the unit of mass, primarily because it is of convenient magnitude, but also because of the manifest advantage of introducing the metric system wherever no practical difficulties interfere. It happens that the two measures which are given in grams are of categories unfamiliar alike to the engineer and the general reader, so that the gram unit encounters no conflicting habit of thought. One measure is the mass of a grain of sand or a pebble, the other the mass of the débris carried by a stream in a second.

The unit of time, for the indication of rates, is one second. Velocity is given in distance per second, ft./sec.; discharge in volume per second, $\text{ft.}^3/\text{sec.}$; and load in mass per second, gm./sec.

In hydraulic and hydrodynamic treatises slope of streams is measured by the quotient of fall by distance, or the tangent of its angle, and the unit slope is taken as 45°. For practical purposes this unit is inconvenient because it transcends experience, and engineers commonly avoid it by speaking of slope in percentage or in fractions of 1 per cent, thus making 1 per cent the actual unit. For most purposes I find the smaller unit most convenient, but I have occasional use for the larger unit and shall accordingly use both. To avoid confusion the symbol S will be used with the smaller unit, and where discrimination is important it will be called *per cent slope*, while the symbol s will be used with the larger unit. $S=100\ s$.

TERMS.

Load.—The quantity of débris transported by a stream through any cross section in a unit of time is its *load* at that section. A part is carried in suspension and a part by traction, but as we are here concerned with traction only, the tractional load is to be understood when the word is used without specification. Load is measured in grams per second, gm./sec. For certain engineering purposes it is desirable to consider load as volume, not as the sum of the volumes of individual grains, but as the gross space occupied by the débris as a natural deposit. For the débris used in the experiments in stream traction, with the mixture of sizes ordinarily found in a river deposit, the weight of 1 cubic foot is about 50,000 grams, or 110 pounds. The symbol for load is L.

Capacity.—The maximum load a stream can carry is its capacity. It is measured in grams per second, gm./sec. As the work of the laboratory was largely to determine capacity by measuring maximum load, the two terms are to a large extent interchangeable in the discussion of laboratory data, but the distinction is nevertheless important. The symbol for capacity is C.

Capacity is a function of various conditions, such as slope and discharge, and the chief purpose of the laboratory investigation was to discover the relations of capacity to conditions. When a fully loaded stream undergoes some change of condition affecting its capacity, it becomes thereby overloaded or underloaded. If overloaded, it drops part of its load, making a deposit. If underloaded, it takes on more load, thereby eroding its bed. Through these reactions the profiles of stream beds are adjusted, so far as stream beds are composed of débris. If the bed is of rock in place, the underloaded stream can not obtain its complement of débris, but nevertheless it attacks the bed. By dragging débris over the rock it files or corrades the bed of its channel. It is a general fact that the loads of streams flowing on bedrock are less than their capacities.

Competence.—Under certain combinations of controlling factors capacity is zero or negative. If then some one factor be changed just enough to render capacity positive, that factor in its new condition is said to be *competent*, or else to be a measure of the stream's competence. For example, a stream at its low stage can not move the débris on its bed; with increase of discharge a velocity is acquired such that traction begins; and the discharge is then said to be competent. A stream flowing over a too gentle slope has no capacity, but coming to a steeper slope it is just able to move débris; the steeper slope is said to be competent. A current flowing over débris of various sizes transports the finer but can not move the coarser; the fineness of the débris it can barely move is the measure of its competence.

Discharge.—The quantity of water passing through any cross section of a stream in a unit of time is the *discharge* of the stream at that point. It is measured in cubic feet per second, $ft.^3/sec.$ The symbol is Q.

Slope.—The inclination of the water surface in the direction of flow is known as the slope of the stream. It is the ratio which fall, or loss of head, bears to distance in the direction of flow. Per cent slope, as explained on page 34, is numerically 100 times as great, being the fall in a distance of 100 units. The terms slope and per cent slope are also applied in this report to the inclination of the bed of the channel.

Size of débris.—The relative magnitude of the débris particles making up the load may be considered from two opposed viewpoints. Thus we may say that the load varies inversely with the coarseness of the débris, or that it varies directly with the fineness. The second viewpoint is here preferred because it conduces to symmetry in formulation. Two very different measures of fineness have been considered, and on page 21 the material of the laboratory is listed under both. One defines fineness by the number of particles which, placed side by side, occupy the linear space of 1 foot. The other defines it by the number of particles required to fill the space of 1 cubic foot. *Linear fineness* is the more readily conceived, because it appeals to vision. *Bulk fineness* is the more easily determined. The symbol of linear fineness is F, of bulk fineness F_2.

Form ratio.—Of the variable factors which in combination produce the multifarious channel forms of natural streams, the laboratory dealt extensively with but a single one, the relation of depth to width. The relation is a simple ratio, and either of the two terms might be made the divisor. The width has been chosen because, as in the case of fineness its selection conduces to symmetry in formulation. The ratio $\frac{\text{depth of stream}}{\text{width of channel}}$ will be called *form ratio*. Its symbol is R.

Duty and efficiency.—Capacity varies with discharge, but is not proportional to it. The load which may be borne by a unit of discharge varies with the discharge and also with the other conditions. It is the capacity per unit discharge, or the quotient of capacity by discharge, and will be called the *duty*. The symbol is U.

Capacity varies also with slope but is not proportional to it. As the product of discharge by slope (by the acceleration of gravity) measures the stream's potential energy per unit time per unit distance, capacity also varies with the energy but is not proportional to it. The load which may be borne by a unit of discharge on a unit slope varies with all the conditions of transportation. It is the capacity per unit discharge and unit slope, or the quotient of capacity by the product of discharge and slope, and will be called the *efficiency*. It is a measure of the stream's potential work of transportation in relation to its potential energy. Its symbol is E.

The primary definition of efficiency in mechanics is the ratio of work done to energy expended; it implies that the work may be expressed in the same unit as energy. The ratio is always less than unity. But there is an important secondary use of the term, applied to cases in which the result accomplished can not be expressed in terms of energy. In such cases the ratio may have any magnitude, as it arises from the comparison of incongruous quantities. It does not measure economy of energy but relative accomplishment in respect to any condition selected for comparison. As capacity for transportation is not statable in units of energy, the use of the term efficiency in this connection falls under the second definition.

Symbols.—An index of symbols, with brief definitions and references to pages for fuller definition, may be found on page 13.

TABLE OF OBSERVATIONS ON STREAM TRACTION.

The observations on stream traction are presented in Table 4. As the original notes are voluminous, certain combinations and reductions were made before tabulation. The reduction of the slope observations involved discrimination, and the mode of reduction is therefore described below. Each horizontal line of the table contains the record of a single experiment.

The observations are arranged according to (1) fineness of débris, (2) width of channel, (3) discharge, (4) load and slope. The categories of fineness begin with single sizes, taken in order from fine to coarse, and follow with mixtures; they constitute subtables, each designated by a letter in parentheses. The arrangement by load and slope is approximate only. In a general way the sequences of load and slope are parallel, each increasing as the other increases, but the data are not perfectly harmonious, and where the two sequences differ the arrangement is somewhat irregular.

The first column, for all divisions of the table except (J), gives width of trough; the second, discharge. The third, fourth, and fifth pertain to load and give, respectively, the load as measured by débris fed at the head of the trough, the load as measured by débris caught at the outfall end, and the period, in minutes, during which débris was collected at the outfall end. The precision of measurement is probably somewhat higher where the period is relatively long.

The next three columns pertain to slope. The sixth contains the slope, in per cent, of the water surface; the seventh, the slope of the bed of débris as shaped by the current; and the eighth, the extreme distance between points at which were made observations used in computing the slope or slopes. Nearly all the experiments for which the recorded distance is 16 feet or less were made in the shorter trough, of which the gross length was 31.5 feet, the distance between the débris-feeding apparatus and the débris-arresting apparatus being 24.5 feet. The experiments for which the recorded distance exceeds 16 feet were made in the longer trough, the distance from the feeding station to the collecting station being at least 16 feet longer than the space covered by the observations used in the computation.

The ninth column shows the depth at a single point as measured by the gage (see p. 21); the tenth gives the mean depth as estimated from the records of water profile and bed profile (see p. 25).

In the eleventh column, headed "Character of bed," a generalization is given from notes on the mode of transportation, the condition of the water surface during the run, and the condition of the bed of débris after the withdrawal of the water. The original notes are somewhat varied in scope and nomenclature, and it seemed best to make the tabulated record more simple. The words *dunes*, *smooth*, and *antidunes* denote the three modes of traction described on pages 30–33. The word *transition* is used where the mode of traction was intermediate between one of the rhythmic modes and the smooth mode, and also where different modes of traction obtained in different parts of the trough.

In the final column the word *free* indicates that the contractor (p. 25) was not used, but the experiment trough retained its full width to the end.

The reduction of the slope observations was preceded by a careful study of them with reference to their systematic and accidental errors. As a result of that study certain criteria of exclusion were adopted, by means of which, it is thought, the influence of systematic errors was materially reduced. The criteria were applied through an inspection of the plotted profiles of water surface and débris bed. The observations excluded were those believed to be much affected either by the peculiar conditions near the head of the trough or by the peculiar conditions near the outfall end, so that the retained observations constituted a continuous series covering the middle.

The observations to be reduced were ascribed equal weights. They consisted of a series of level readings (h_0, h_1, h_2 . . . h_{n-1}, h_n), each giving the vertical distance of a point of the débris surface, or of the water surface, below a horizontal plane of reference, together with the horizontal distances of the same points from an initial point in the axis of the trough. The observed points being at equal intervals along the trough, and the zero of distances being made coincident with the first of the observed points, the horizontal distances may be represented by 0, l, $2l$, . . . $(n-1)l$. The following formula[1] was used to compute the slope, the number of terms in numerator or denominator being $\frac{n}{2}$ when n was an even number, and $\frac{n+1}{2}$ when n was odd.

$$S=\frac{100}{l}\cdot\frac{(h_n-h_0)n+(h_{n-1}-h_1)(n-2)+(h_{n-2}-h_2)(n-4)+\ .\ .\ .}{n^2+(n-2)^2+(n-4)^2+\ .\ .\ .}\qquad(1)$$

The numerical operations were simple.

In division (J) of the table the arrangement is somewhat different, and a column is added at the left. The division records experiments made with débris prepared by mixing, in definite proportions, two or more of the grades of débris to which the preceding divisions pertain. The notation adopted to designate these mixtures is analogous to that for chemical compounds, subscript figures being used to indicate approximate proportions. This notation, together with the more precise indication of the proportions, is given in the left-hand column.

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[1] Essentially a least-squares formula, although developed from apparently independent considerations.

TABLE 4 (A).—*Observations on load, slope, and depth, with débris having 25,200 particles to the gram, or grade (A).*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.^{3}/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.66	0.093	27	24	5	1.12	1.22	16	0.065	0.083		Contracted.
		67	74	5		2.14	16			Antidunes	Do.
	.182	19	18	10		.69	16	.126		Smooth	Contracted.
		93	96	4		1.59	14	.095		Antidunes	Do.
	.545	59	58	5	.56	.55	16	.272	.284	Smooth	Contracted.
		147	157	3		1.07	16			Antidunes	Do.
1.00	.182	10.5	9.4	10	.58	.53	16	.118	.136	Dunes	Contracted.
		151	155	3		2.04	16			Antidunes	Do.
	.363	20	19	8		.42	14	.175		Transition	Contracted.
		240	245	3		1.64	16			Antidunes	Do.
	.734	52	51	4		.44	14	.264		Smooth	Contracted.
		317	317	3		1.19	16			Antidunes	Do.
1.32	.182	12	12	10	.65	.63	16	.091	.106	Dunes	Contracted.
		17	18	10	.83	.75	16	.084	.091	do	Do.
		18	17	10		.73	16	.075		do	Do.
		23	21	8	.80	.79	16	.080	.083	do	Do.
		37	38	6		.99	16	.063	.087	Transition	Do.
		50	51	5	1.11	1.10	16	.058	.079	Antidunes	Do.
		75	68	5		1.37	16	.061		[Antidunes]	Do.
		73	73	5		1.41	16	.060		Antidunes	Do.
		129	120	5		1.79	16			[Antidunes]	Do.
		120	135	3		1.86	16			do	Do.
	.363	7.3	8.9	8	.37	.27	16	.191	.195	Dunes	Contracted.
		42	38	6	.60	.51	16	.124	.131	Transition	Do.
		45	41	5		.58	16	.115			Do.
		44	43	5		.67	16	.112			Do.
		65	74	4		.84	16	.112			Do.
		69	76	5	.77	.90	16	.130		Transition	Do.
		125	133	4		1.18	16	.115		Antidunes	Do.
		121	140	5		1.14	16	.106		do	Do.
			177	4		1.43	16	.089		do	Do.
		214	202	4		1.55	16	.097		[Antidunes]	Do.
			240	4		1.65	16			do	Do.
	.734	38	38	5	.35	.35	10		.267	Dunes	Contracted.
		82	84	4	.53	.48	16	.205	.207	Smooth	Do.
		86	89	4		.51	16	.198		do	Do.
		127	156	4		.73	16	.190		Antidunes	Do.
		151	154	3		.83	16			do	Do.
		191	192	3		.81	16			[Antidunes]	Do.
		176	215	3		.97	16			Antidunes	Do.
			240	3		.95	16			do	Do.
			327	3		1.13	16			do	Do.
			365	3		1.24	16			[Antidunes]	Do.
1.96	.363	8.1	8.7	6	.50	.36	16	.179	.187	Dunes	Contracted.
		20	20	6		.41	16	.118			Do.
		19	21	6	.69	.55	16	.118	.129		Do.
		33	32	5	.67	.60	16	.103	.107		Do.
		58	60	5	.78	.78	16	.090	.097		Do.
		81	92	5	.97	.94	16	.082	.084	Antidunes	Do.
		128	127	5		1.10	16	.073		do	Do.
		143	128	5		1.17	16	.077		do	Do.
		128	144	4		1.18	16	.075		do	Do.
		192	179	4		1.38	16	.072		[Antidunes]	Do.
		215	193	4		1.50	16	.076		do	Do.
		227	218	4		1.59	16	.067		do	Do.
			264	3		1.73	16	.069		Antidunes	Do.
			283	3		1.77	16	.070		[Antidunes]	Do.
	.734	7.7	8.3	10	.18	.18	16	.283	.293		Contracted.
		32	33	6		.36	12	.180			Do.
		74	83	4		.45	16	.156			Do.
		70	80	5	.58	.49	16	.156	.152	Smooth	Do.
		105	105	5	.79	.56	16	.137	.146	do	Do.
		148	163	4		.79	16	.142		Transition	Do.
			167	4		.75	16	.135			Do.
		214	179	3		.94	16	.129		Antidunes	Do.
		221	231	3		.98	16	.135		[Antidunes]	Do.
			279	3		1.01	16	.130		Antidunes	Do.
	1.119	94	91	4	.30	.45	16	.220	.214	Smooth	Contracted.
		99	102	4		.39	16	.207		[Smooth]	Do.
		186	130	4	.33	.57	16	.194	.201	Smooth	Do.
		169	188	3		.59	16	.196		do	Do.
		180	221	3		.63	16	.182		do	Do.
		198	229	3		.60	16	.187			Do.
		221	258	4		.81	16	.165		Transition	Do.
			291	3		.79	16	.179		Antidunes	Do.
			341	3		.95	16			do	Do.
			346	3		1.02	16	.176		do	Do.

TABLE 4 (B).—*Observations on load, slope, and depth, with débris having 15,400 particles to the gram, or grade (B).*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³ sec.*	*Gm. sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.23	0.093		4.0	9		0.85	16	0.192		Transition	Free.
			6.7	7		.94	16	.184		do	Do.
			8.1	7		1.01	16	.174		Smooth	Do.
			20	7		1.49	16	.146		do	Do.
			33	7		2.12	16			Antidunes	Do.
	.182		4.0	10		.73	16	.364		Dunes	Free.
			18	6		1.12	16	.284		Smooth	Do.
			31	5		1.55	16	.230		Transition	Do.
			32	7		1.55	16	.232		do	Do.
.44	.093		5.3	6		.73	16	.136		Dunes	Free.
			11	7		.90	16	.110		Smooth	Do.
			18	4		1.18	16	.093		Transition	Do.
			34	7		1.62	16	.070		Antidunes	Do.
			53	5		2.31	16	.072		do	Do.
			64	4		2.38	16	.068		do	Do.
	.182		8.5	7		.50	16	.194		Transition	Free.
			16	5		.75	16	.177		Smooth	Do.
			27	6		.98	16	.146		Transition	Do.
			73	8		1.66	16			Antidunes	Do.
			76	4		1.73	16	.139		do	Do.
.66	.093		5.1	8		.75	16	.089		Dunes	Free.
			9.2	6		.84	16	.080		do	Do.
			17	7		1.23	16	.060		Smooth	Do.
			15	9		1.32	12	.059		Transition	Do.
			22	5		1.41	16	.058		do	Do.
			28	5		1.47	16	.050		do	Do.
			34	5		1.63	16	.056		do	Do.
			41	5		2.01	16	.054		do	Do.
			53	5		2.09	16	.049		Antidunes	Do.
			57	5		2.17	16	.058		do	Do.
			93	7		2.96	16	.037		do	Do.
	.182	4.8	4.2	8	0.32	.35	16	.175	0.183	Dunes	Contracted.
		3.5	6.0	8	.37	.36	16	.175	.183	do	Do.
		14	12	7		.69	16				Do.
		15	16	6		.68	16	.137			Do.
		23	20	8		.66	16	.113			Free.
		27	21	4		.72	16	.110			Do.
		24	19	8		.81	16	.107		Smooth	Do.
		42	42	7		.98	16	.113			Do.
		47	39	6		1.06	16	.101			Do.
		41	44	9		1.18	16				Do.
		51	47	8		1.17	16	.112			Do.
			55	5		1.32	16	.107		Transition	Do.
		55	55	8		1.35	16				Do.
			55	5		1.36	16	.103		do	Do.
			67	7		1.51	16			Antidunes	Do.
		81	72	7		1.54	16			do	Do.
			88	4		1.51	16	.091		[Antidunes]	Do.
			105	5		2.00	16	.082		Antidunes	Do.
			112	6		1.88	16	.083		[Antidunes]	Do.
			119	6		2.05	16	.077		do	Do.
		166	126	4		2.24	16			Antidunes	Do.
			139	5		2.19	16	.115		[Antidunes]	Do.
			159	5		2.46	16	.096		do	Do.
			169	5		2.79	16	.082		do	Do.
			213	4		3.14	16			do	Do.
			236	3		3.06	16			do	Do.
			254	3		2.91	16			do	Do.
			268	4		2.93	16			do	Do.
			377	3		4.03	16			do	Do.
	.363	29	29	5		.51	16	.216	.221	Transition	Contracted.
		44	40	8		.68	16	.212		do	Free.
		52	39	6		.69	16	.205		do	Do.
		58	49	6		.75	16	.202		Smooth	Do.
		73	55	5		.80	16	.188		do	Do.
			77	4		.98	16	.178		Transition	Do.
			91	5		.99	16	.189		Antidunes	Do.
			104	5		1.14	16	.191		do	Do.
			148	4		1.54	16	.177		[Antidunes]	Do.
			152	5		1.43	16	.155		do	Do.
			164	4		1.63	16			do	Do.
			167	5		1.66	14	.158		do	Do.
			186	3		1.71	16			do	Do.
			226	4		1.81	16			do	Do.
	.545		5.8	6	.18	.21	16	.471	.472	Dunes	Contracted.
		16	16	9		.23	14	.367		do	Do.
		34	35	5	.47	.46	14	.291	.300	Transition	Do.
		64	54	8		.63	16	.292		do	Free.
		67	68	6		.74	16	.258		do	Do.
		79	81	6		.72	14	.260		Smooth	Do.
		108	104	5		.87	16	.220			Do.
		105	111	5		.89	16	.226		Transition	Do.
			132	5		1.00	16	.230		Antidunes	Do.
			169	5		1.32	16	.231		do	Do.
			242	3		1.81	16			[Antidunes]	Do.
			271	3		1.81	16			do	Do.
			304	3		1.79	16			do	Do.

TABLE 4 (B). *Observations on load, slope, and depth, with débris having 13,400 particles to the gram, or grade (B)*—Con.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.00	0.182	9.9	11	5		0.61	16	0.106		Dunes	Contracted.
		9.9	13	5		.61	16	.102			Do.
			28	6		.97	16	.073		Transition	Free.
			39	5		1.15	16	.081		do	Do.
			51	5		1.29	16	.075		Smooth	Do
			98	4		1.87	16	.060		Antidunes	Do
			116	4		2.14	16	.067		do	Do.
			157	3		2.43	16	.066		do	Do.
			182	4		2.63	16	.070		[Antidunes]	Do.
	.363	0	0		0.030	.044	60	.475		Dunes forming	Contracted.
		2.1	1.3	390	.18	.16	60	.344	.323	[Dunes]	Do.
		1.9	1.6	360	.17	.16	60	.321	.321	do	Do.
		6.4	6.2	60		.28	48			do	Do.
		6.8	6.8	44	.27	.31	44	.278	.271	do	Do.
		10.5	7.2	5		.23	16	.214	.244	do	Do.
		9.6	9.4	71		.33	40	.224		do	Do.
		8.7	9.7	6		.29	16	.208		do	Do.
		9.3	11	62		.31	44	.254		Dunes	Do.
		18	21	30	.42	.43	49	.188	.193		Do.
		25	25	15	.43	.49	36	.195	.176		Do.
		28	28	4		.54	16	.164			Do.
		37	49	8		.63	32			Transition	Do.
			46	4		.78	14	.154		Smooth	Free.
			55	9		.65	12	.150		do	Do.
			79	4		1.00	16	.120		Antidunes	Do.
			153	4		1.51	16	.107		do	Do.
			206	4		1.66	16	.129		do	Do.
			218	3		1.78	16	.112		do	Do.
			268	3		2.00	16			do	Do.
			305	3		2.14	16			[Antidunes]	Do.
			347	3		2.28	16			do	Do.
	.545		107	5		.79	12	.194		Smooth	Free.
			117	5		.83	16	.167		Transition	Do.
			167	4		1.16	16	.157		Antidunes	Do.
			199	3		1.31	16	.169		do	Do.
			219	3		1.29	16			[Antidunes]	Do.
			274	3		1.46	16			Antidunes	Do.
			306	3		1.63	16	.144		do	Do.
			315	3		1.65	16			[Antidunes]	Do.
			396	2		1.84	16			do	Do.
			504	2		2.10	16			do	Do.
	.734	0	0			.012	49	.735	.740	Dunes forming	Contracted.
		3.9	4.7	60	.14	.15	40	.497	.500		Do.
		4.7	4.9	90	.14	.18	36	.496	.497		Do.
		18	17	20	.25	.26	28	.332	.334		Do.
		37	38	10	.36	.38	24	.282	.267		Do.
		56	52	10	.41	.48	28	.257	.256		Do.
			54	8		.45	15	.257		Transition	Free.
		56	59	10		.50	28	.257			Contracted.
			60	7		.53	16	.262		Transition	Free.
			62	9		.44	16	.257		do	Do.
		84	80	5	.31	.54	28	.250	.241		Contracted.
			102	5		.68	16	.237		Transition	Free.
			188	5		.92	16	.207		Smooth	Do.
			244	3		1.16	16			Antidunes	Do.
			305	3		1.30	16			do	Do.
			370	2		1.46	16			[Antidunes]	Do.
			416	2		1.72	16			do	Do.
			433	2		1.56	16			do	Do.
1.32	.182	7.3	5.2	8	.40	.40	16	.129	.126	Dunes	Contracted.
		5.8	5.3	8		.45	16			[Dunes]	Do.
			14	6		.80	16	.081		Dunes	Free.
			17	6		.98	16	.061		do	Do.
			34	6		1.12	16	.063		Transition	Do.
			27	9		1.18	12	.057		do	Do.
			43	6		1.22	16	.056		Smooth	Do.
			56	6		1.41	16	.053		Transition	Do.
			68	6		1.66	16	.041		do	Do.
			81	5		1.71	16	.051		do	Do.
			80	5		1.77	16	.038		do	Do.
			93	7		1.88	16	.045		Antidunes	Do.
			115	4		2.11	16	.058		do	Do.
			127	4		2.33	16			do	Do.
			142	4		2.32	16	.037		[Antidunes]	Do.
			152	4		2.46	16	.039		do	Do.
	.363	8.3	5.2	5	.21	.25	16	.227	.220	Dunes	Contracted.
		8.7	7.9	9	.42	.26	16	.203	.197	[Dunes]	Do.
		17	17	9	.53	.43	16	.153	.163	do	Do.
		19	16	9	.64	.43	16	.147	.163	do	Do.
			22	6		.47	14	.131		Dunes	Free.
			22	6		.66	16	.128		[Dunes]	Do.
			25	4		.69	14	.124		Dunes	Do.
			38	6		.82	12	.109		do	Do.
			89	7		1.07	16	.098			Do.
			104	6		1.20	16	.099			Do.
			136	5		1.28	16	.089		Antidunes	Do.
			131	5		1.33	16	.072		do	Do.
			134	5		1.37	16	.098		[Antidunes]	Do.

TABLE 4, B.—*Observations on load, slope, and depth, with débris having 15,400 particles to the gram, or grade (B)*.—Con.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profile.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.32	0.363		162	7		1.54	16	0.092		Antidunes	Free.
			173	5		1.63	16	.082		do	Do.
			257	5		1.90	16			Antidunes	Do.
			261	3		2.12	16			do	Do.
	.545	31	29	5	[illegible]	.47	12	.205	[illegible]	Dunes	Contracted.
		40	55	4		.54	14	.162	[illegible]	do	Do.
		50	54	4	[illegible]	.61	14	.154	[illegible]	do	Do.
		82	89	4		.76	16	.139			Do.
		82	92	5		.79	16	.141		Smooth	Do.
			105	5		.75	14	.148		do	Free.
			104	4		.84	16	.158		Transition	Do.
			147	4		.98	16	.141		Antidunes	Do.
			218	3		1.28	16	.196		do	Do.
			264	4		1.49	16			do	Do.
			278	3		1.49	16			[Antidunes]	Do.
			301	5		1.85	16			do	Do.
	.734	26	30	5	.33	.31	12	.280	[illegible]		Contracted.
			39	7		.41	16	.226		Transition	Free.
			55	6		.70	16	.219		do	Do.
			56	6		.50	16	.195		do	Do.
			63	5		.73	16	.206		do	Do.
			90	5		.58	16	.199		Smooth	Do.
			129	6		.87	16	.174		do	Do.
			136	6		.67	16	.170		do	Do.
			134	5		.78	16	.172		do	Do.
			144	4		.85	16	.165		Transition	Do.
			167	4		.90	16	.173		do	Do.
			178	5		.96	16	.169		Antidunes	Do.
			182	5		.92	16	.166		do	Do.
			204	4		1.01	16			do	Do.
			255	3		1.10	16			[Antidunes]	Do.
			268	3		1.14	16			do	Do.
			280	3		1.17	16			do	Do.
			341	3		1.35	16			do	Do.
			342	3		1.45	16			do	Do.
			383	2		1.51	16			do	Do.
			485	2		1.65	16			do	Do.
			516	3		1.66	16			do	Do.
1.96	.363	8.1	7.5	8	.47	.31	16	.102		Dunes	Contracted.
			18	8		.65	16	.104			Free.
			25	12		.62	16	.110			Do.
			36	23		.59	14	.070			Do.
		47	40	12		.77	14	.087			Do.
			44	8		.92	16	.080		Smooth	Do.
			59	4		1.01	16	.059		Transition	Do.
		80	66	8		1.03	16	.068			Do.
			68	6		1.07	16	.078		Transition	Do.
			96	7		1.21	16	.062		do	Do.
			137	5		1.45	16	.063		Antidunes	Do.
			147	3		1.48	16	.044		do	Do.
			177	3		1.62	16	.050		[Antidunes]	Do.
			186	3		1.64	16			do	Do.
			214	3		1.81	16			do	Do.
			249	3		2.00	16	[illegible]		do	Do.
	.545		53	23		.54	16	.152			Free.
		86	59	6		.70	16	.127		Smooth	Do.
		75	70	5		.69	16	.130			Do.
			72	18		.71	16	.126			Do.
		109	90	2		.78	16	.091			Do.
			89	5		.80	16	.111		Transition	Do.
			94	4		.98	16	.115		do	Do.
			106	4		.97	16			do	Do.
			144	4		1.12	16	.069		do	Do.
			217	4		1.39	16				Do.
			264	3		1.60	16	.095		Antidunes	Do.
			299	3		1.58	16			[Antidunes]	Do.
			307	3		1.54	16			Antidunes	Do.
			303	3		1.61	16			[Antidunes]	Do.
			356	3		1.73	16			Antidunes	Do.
	.734	7.7	7.6	6	.31	.23	10	.250	.257	Dunes	Contracted.
		38	40	5	.40	.27	16	.188	.196		Do.
		35	40	8		.44	12	.171			Free.
		101	66	8	.44	.53	14	.161			Do.
		89	88	4		.59	16				Do.
			98	9		.64	14	.139			Do.
			103	6		.56	14	.148			Do.
			186	3		.80	16			Antidunes	Do.
			185	3		1.05	16			do	Do.
		245	198	3		1.03	16			[Antidunes]	Do.
			239	4		1.05	16	.150		Antidunes	Do.
			332	3		1.40	16			[Antidunes]	Do.
			341	3		1.39	16	.146		Antidunes	Do.
			352	3		1.38	16			[Antidunes]	Do.
			348	3		1.45	16	.124		Antidunes	Do.
			469	2		1.64	16			[Antidunes]	Do.
			520	2		1.87	16			do	Do.

TABLE 4 (B).—*Observations on load, slope, and depth, with débris having 13,400 particles to the gram, or grade (B)*—Con.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.96	1.119	6.5	6.4	10	0.21	0.19	16	0.411	0.406	Dunes	Contracted.
		14	13	10	.28	.18	16	.353	.375	[Dunes]	Do.
		29	32	11	.37	.32	16	.345	.337	Dunes	Do.
		53	59	4	....	.28	12	.229	....	Transition	Do.
		112	109	8	....	.59	16	.315	....	....	Free.
		....	110	6	....	.61	16	.211	....	Smooth	Do.
		126	129	5	....	.65	12	.188	....	[Smooth]	Do.
		....	191	4	....	.72	16	.188	....	Smooth	Do.
		....	230	4	....	.73	16	.184	....	....	Do.
		....	317	3	....	.91	16	.187	....	Transition	Do.
		....	310	2	....	1.00	16	.176	....	....	Do.
		....	356	2	....	.93	16	....	....	....	Do.
		....	355	2	....	.98	16	....	....	....	Do.
		....	406	3	....	1.13	16	....	....	....	Do.
		....	418	3	....	1.31	16	.145	....	Antidunes	Do.

TABLE 4 (C).—*Observations on load, slope, and depth, with débris having 5,460 particles to the gram, or grade (C).*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.44	0.093	....	3.2	7	....	0.64	16	0.161	....	Dunes	Free.
		....	5.3	5	....	.85	16	.141	....	Transition	Do.
		....	9.4	5	....	.94	16	.131	....	Smooth	Do.
		....	12	5	....	1.01	16	.122	....	do	Do.
		....	19	7	....	1.26	16	.117	....	do	Do.
		....	26	4	....	1.45	16	.111	....	do	Do.
		....	35	5	....	1.59	16	.111	....	do	Do.
		....	34	4	....	1.71	16	.100	....	do	Do.
		....	46	4	....	2.24	16	....	....	Antidunes	Do.
	.182	....	9.7	6	....	.61	16	.235	....	Dunes	Free.
		....	14	6	....	.70	16	.233	....	Transition	Do.
		....	38	6	....	1.33	16	.168	....	Smooth	Do.
		....	43	5	....	1.32	16	.176	....	do	Do.
		....	47	4	....	1.38	16	.172	....	do	Do.
		....	51	5	....	1.52	16	.153	....	do	Do.
		....	97	3	....	2.16	16	.138	....	Antidunes	Do.
.66	.093	....	3.5	10	....	.54	16	.108	....	Dunes	Free.
		....	8.6	13	....	.79	16	.084	....	[Dunes]	Do.
		....	10	7	....	.98	16	.077	....	Dunes	Do.
		....	15	6	....	.97	16	.078	....	do	Do.
		....	15	6	....	1.05	16	.075	....	do	Do.
		....	17	6	....	1.05	16	.077	....	do	Do.
		....	16	6	....	1.11	16	.073	....	Transition	Do.
		....	22	6	....	1.36	16	.066	....	Smooth	Do.
		....	35	5	....	1.56	16	.063	....	do	Do.
		....	48	4	....	1.98	16	.055	....	Antidunes	Do.
		....	61	4	....	2.38	16	.050	....	do	Do.
		....	74	3	....	2.52	16	.052	....	[Antidunes]	Do.
		....	100	3	....	3.02	16	....	....	Antidunes	Do.
		....	109	5	....	3.41	16	....	....	do	Do.
		....	142	3	....	3.73	16	....	....	do	Do.
		....	146	3	....	3.79	16	....	....	do	Do.
		....	156	3	....	4.04	16	....	....	do	Do.
	.182	2.0	2.3	420	0.29	.24	64	.242	0.238	[Dunes]	Contracted.
		....	9.7	11	....	.54	16	.136	....	do	Free.
		....	16	8	....	.64	16	.124	....	do	Do.
		....	18	7	....	.76	16	.132	....	Dunes	Do.
		....	18	7	....	.72	16	.127	....	do	Do.
		....	28	6	....	.94	16	.117	....	Transition	Do.
		....	39	5	....	1.16	16	.096	....	Smooth	Do.
		....	45	7	1.20	1.17	16	.099	.110	[Smooth]	Do.
		....	72	5	....	1.54	16	....	....	Smooth	Do.
		....	78	8	1.69	1.57	16	.089	.093	do	Do.
		....	105	4	....	1.95	16	....	....	Transition	Do.
		....	113	4	....	2.24	16	.062	....	Antidunes	Do.
		....	123	4	....	2.32	16	....	....	do	Do.
		....	133	4	....	2.33	16	....	....	do	Do.
		....	146	3	....	2.58	16	....	....	do	Do.
		....	155	4	....	2.54	16	....	....	do	Do.
		....	163	3	....	2.63	16	....	....	do	Do.
		....	190	4	....	2.82	16	....	....	[Antidunes]	Do.
		....	205	3	....	2.99	16	....	....	do	Do.
		....	220	3	....	3.05	16	....	....	do	Do.
		....	217	3	....	3.20	16	....	....	do	Do.
		....	246	3	....	3.45	16	....	....	do	Do.
	.363	....	22	5	....	.44	16	.241	....	Dunes	Free.
		....	32	5	....	.64	16	.222	....	Transition	Do.
		....	34	6	....	.70	16	.211	....	do	Do.
		38	37	4	....	.61	16	.213	....	[Transition]	Contracted.

TABLE 4 (C).—*Observations on load, slope, and depth, with débris having 5,460 particles to the gram, or grade (C)*—Con.

Width.	Discharge.	Load.			Slope.		Depth.			Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.^{3}/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.66	0.363	35	35	4	.....	0.63	16	0.216	.....	Transition	Contracted.
		37	40	4	.....	.66	16	.212	.....	[Transition]	Do.
		.....	39	5	.....	.67	16	.205	.....	Transition	Free.
		.....	54	5	.....	.87	16	.186	.....	Smooth	Do.
		.....	78	6	.....	.99	14	.174	.....	do	Do.
		.....	83	5	.....	1.04	16	.167	.....	do	Do.
		82	98	3	.....	1.08	14	.168	.....	Transition	Contracted.
		89	99	3	.....	1.07	16	.173	.....	.....	Do.
		92	97	3	.....	1.08	16	.164	.....	.....	Do.
		.....	121	5	.....	1.19	14	.174	.....	Smooth	Free.
		.....	121	4	.....	1.23	14	.168	.....	do	Do.
		.....	134	4	.....	1.41	16	.161	.....	Transition	Do.
		.....	161	3	.....	1.71	16	.....	.....	Antidunes	Do.
		.....	182	3	.....	1.87	16	.....	.....	do	Do.
		.....	183	3	.....	1.91	16	.....	.....	do	Do.
		.....	228	3	.....	1.97	14	.....	.....	[Antidunes]	Do.
		.....	241	3	.....	2.04	16	.....	.....	do	Do.
		.....	245	3	.....	2.08	16	.165	.....	do	Do.
		.....	240	3	.....	2.11	16	.....	.....	do	Do.
		.....	281	3	.....	2.29	16	.....	.....	do	Do.
		.....	292	3	.....	2.57	16	.....	.....	do	Do.
	.545	2.8	2.8	410	0.15	.20	56	.579	0.577	[Dunes]	Contracted.
		.....	36	7	.....	.54	16	.312	.....	Dunes	Free.
		44	45	4	.....	.51	16	.288	.....	.....	Contracted.
		46	48	4	.....	.56	14	.284	.....	.....	Do.
		46	49	4	.....	.57	16	.278	.....	Transition	Do.
		45	47	4	.....	.58	16	.288	.....	[Transition]	Do.
		.....	41	7	.....	.60	16	.303	.....	.....	Free.
		.....	47	8	.....	.60	16	.308	.....	Transition	Do.
		.....	53	8	.....	.57	16	.300	.....	do	Do.
		.....	76	4	.....	.78	16	.255	.....	do	Do.
		.....	88	3	.....	.82	16	.260	.....	do	Do.
		111	117	3	.....	.96	16	.223	.....	do	Contracted.
		119	115	3	.....	.98	16	.223	.....	[Transition]	Do.
		117	121	3	.....	.99	16	.228	.....	do	Do.
		.....	130	3	.....	1.01	16	.242	.....	Smooth	Free.
		.....	151	5	.....	1.12	16	.226	.....	do	Do.
		.....	152	4	.....	1.12	16	.239	.....	[Smooth]	Do.
		.....	162	5	.....	1.21	16	.222	.....	Smooth	Do.
		.....	196	4	.....	1.53	16	.234	.....	Antidunes	Do.
		.....	239	4	.....	1.56	16	.....	.....	[Antidunes]	Do.
		.....	241	3	.....	1.64	16	.....	.....	do	Do.
		.....	252	3	.....	1.69	14	.....	.....	Antidunes	Do.
		.....	275	3	.....	1.73	14	.....	.....	[Antidunes]	Do.
		.....	346	3	.....	2.04	16	.....	.....	do	Do.
	.734	67	61	4	.....	.62	14	.327	.....	[Transition]	Contracted.
		67	64	4	.....	.62	14	.318	.....	do	Do.
		67	67	4	.....	.58	16	.320	.....	do	Do.
		152	168	3	.....	.99	14	.263	.....	do	Do.
		164	163	3	.....	1.04	16	.277	.....	Transition	Do.
1.00	.182	.....	7.6	9	.....	.54	16	.117	.....	Dunes	Free.
		.....	11	12	.....	.57	16	.116	.....	do	Do.
		.....	16	9	.....	.73	16	.110	.....	do	Do.
		.....	17	5	.....	.75	16	.107	.....	do	Do.
		.....	18	5	.....	.74	16	.108	.....	do	Do.
		28	26	10	.....	.91	16	.....	.....	do	Do.
		39	41	8	.....	1.10	16	.....	.....	do	Do.
		53	54	6	.....	1.31	16	.....	.....	Transition	Do.
		53	56	11	.....	1.32	16	.....	.....	do	Do.
		79	70	3	.....	1.52	16	.....	.....	Smooth	Do.
		.....	84	6	.....	1.68	16	.065	.....	do	Do.
		.....	97	4	.....	1.85	16	.062	.....	do	Do.
		105	106	4	.....	1.96	16	.....	.....	Transition	Do.
		.....	114	4	.....	2.07	16	.051	.....	Antidunes	Do.
		.....	128	4	.....	2.24	16	.065	.....	do	Do.
		.....	131	4	.....	2.32	16	.....	.....	do	Do.
		.....	145	3	.....	2.48	16	.....	.....	do	Do.
		.....	166	3	.....	2.66	16	.....	.....	[Antidunes]	Do.
	.363	1.9	1.9	94	.17	.19	48	.322	.326	Dunes	Contracted.
		6.5	5.1	41	.26	.24	48	.266	.275	[Dunes]	Do.
		19	18	10	.42	.42	48	.209	.221	do	Do.
		.....	24	8	.....	.44	16	.187	.....	Dunes	Free.
		.....	30	6	.....	.52	16	.164	.....	do	Do.
		42	39	7	.61	.65	40	.168	.170	.....	Contracted.
		.....	46	6	.....	.73	16	.142	.....	Transition	Free.
		46	48	4	.....	.70	16	.143	.....	[Transition]	Contracted.
		43	48	4	.....	.73	16	.141	.....	Transition	Do.
		.....	58	6	.....	.82	16	.144	.....	do	Free.
		.....	61	5	.....	.83	16	.133	.....	do	Do.
		85	83	8	.....	.95	32	.135	.....	Smooth	Contracted.
		75	81	3	.....	.97	16	.....	.....	[Smooth]	Free.
		85	86	9	.....	.93	32	.123	.....	Smooth	Contracted.
		75	84	3	.....	.96	16	.....	.....	do	Free.
		.....	86	5	.....	.97	16	.133	.....	do	Do.
		.....	104	5	.....	1.09	16	.121	.....	do	Do.
		.....	104	5	.....	1.09	16	.133	.....	do	Do.
		140	124	3	.....	1.25	16	.114	.....	[Smooth]	Contracted.
		158	131	3	.....	1.26	16	.114	.....	do	Do.
		.....	147	5	.....	1.38	16	.115	.....	Smooth	Free.

TABLE 4 (C).—*Observations on load, slope, and depth, with débris having 5,460 particles to the gram, or grade (C)*—Con.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.00	0.363		146	5		1.50	16			Antidunes	Free.
			233	4		1.99	16			do	Do.
			257	3		1.98	16			do	Do.
			256	3		2.10	16			[Antidunes]	Do.
			255	4		2.11	16			do	Do.
			349	3		2.48	16			do	Do.
			362	3		2.65	16			do	Do.
	.545		48	5		.51	16	0.211		Dunes	Free.
			57	5		.53	16	.206		[Dunes]	Do.
		60	68	4		.61	16	.193		Transition	Contracted.
		61	64	4		.62	16	.189		do	Do.
			71	5		.62	16	.193		do	Free.
			107	5		.83	16	.176			Do.
			107	5		.88	16	.175		Smooth	Do.
		146	150	3		1.02	14	.167		do	Contracted.
			153	4		1.05	16	.173		do	Free.
			165	4		1.09	16	.163		do	Do.
			169	5		1.00	16	.160		do	Do.
		158	173	3		1.12	14	.166		[Smooth]	Contracted.
		176	181	3		1.12	14	.160		do	Do.
			205	4		1.28	16	.148		Smooth	Free.
			266	4		1.50	16	.136		Transition	Do.
			315	3		1.60	16			Antidunes	Do.
			292	4		1.70	16			do	Do.
			296	4		1.75	16			do	Do.
			281	3		1.87	16			[Antidunes]	Do.
			355	3		1.95	16			do	Do.
			391	3		1.94	16			do	Do.
			398	3		1.97	16			do	Do.
			431	3		2.17	16			do	Do.
	.734	1.9	1.6	60	0.11	.13	48	.581	0.579	[Dunes]	Contracted.
		2.6	2.1	170	.11	.16	32		.570	do	Do.
		2.6	3.0	180	.16	.14	40		.537	do	Do.
			13	12	.21	.21	56			Dunes	Free.
		13	15	20	.17	.27	40	.459	.467	[Dunes]	Contracted.
			14	12	.26	.33	76	.420	.413	do	Free.
		42	39	8		.34	36	.322		do	Do.
		74	84	4		.58	16	.232		Transition	Contracted.
		76	85	4		.58	14	.241		do	Do.
		103	117	5		.57	36	.261		[Transition]	Do.
			77	4		.61	14	.249		Transition	Free.
			95	6		.59	16	.233		do	Do.
			132	4		.81	16	.221		do	Do.
		160	194	3		.99	16	.194			Contracted.
			181	6		1.01	16	.203		Smooth	Do.
			230	4		1.15	16	.187		do	Do.
			267	4		1.29	16	.199		Transition	Do.
			308	4		1.43	16			Antidunes	Do.
			309	3		1.50	16			do	Do.
			329	3		1.51	16			do	Free.
			444	3		1.78	16			[Antidunes]	Do.
			501	3		2.07	16			do	Do.
	1.119	111	118	3		.57	14	.312		Transition	Contracted.
		114	129	3		.66	14	.305		[Transition]	Do.
		325	348	2		1.17	16	.256		[Smooth]	Do.
		325	370	2		1.22	16	.253		Smooth	Do.
1.32	.182	11	9.6	10	.66	.66	16	.093	.090	Dunes	Contracted.
			7.8	9		.70	12	.100		do	Free.
			13	6		.84	14	.090		do	Do.
			21	5		.98	16	.076		do	Do.
			30	6		1.14	16	.067		Transition	Do.
			43	5		1.24	16	.067		do	Do.
			58	5		1.64	16	.055		Smooth	Do.
			99	5		2.08	16	.040		Transition	Do.
			120	5		2.23	16	.049		Antidunes	Do.
			126	4		2.10	16	.056		[Antidunes]	Do.
			130	4		2.29	16	.051		do	Do.
			141	3		2.34	16	.045		Antidunes	Do.
	.363		8.8	6	.33	.32	16	.163	.174	Dunes	Contracted.
		7.8	10	6	.31	.35	16	.171	.170	do	Do.
		26	26	6	.55	.56	16	.140	.178	[Dunes]	Do.
			27	6		.56	16	.127		Dunes	Free.
			38	5		.72	16	.123		do	Do.
			51	5		.79	16	.122		do	Do.
			60	5		.89	16	.120		Transition	Do.
			85	5		1.07	16	.106		Smooth	Do.
			111	6		1.23	14	.104		do	Do.
			118	5		1.27	16	.100		do	Do.
			130	4		1.32	16	.097		do	Do.
			129	4		1.33	16	.085		do	Do.
			154	4		1.46	16	.090		Transition	Do.
			158	4		1.44	16	.089		do	Do.
			190	3		1.80	16			Antidunes	Do.
			237	3		1.92	16			[Antidunes]	Do.
			264	3		2.14	16			do	Do.
			266	3		2.18	16			Antidunes	Do.
			300	3		2.30	16			[Antidunes]	Do.
			308	3		2.46	16			Antidunes	Do.

Table 4 (C). *Observations on load, slope, and depth, with débris having 5,400 particles to the gram, or grade (C)*—Con.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³ sec.*	*Gm. sec.*	*Gm. sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.32	0.545		36	6		0.56	12	0.186		Dunes	Free.
			55	6		.62	16	.172		do	Do.
			79	5		.69	16	.152		do	Do.
			96	5		.83	16	.152		Transition	Do.
			118	5		.85	16	.141		Smooth	Do.
			159	5		1.10	16	.132		do	Do.
			210	5		1.37	16	.118		Transition	Do.
			248	4		1.57	16			Antidunes	Do.
			256	3		1.58	16			[Antidunes]	Do.
			340	3		1.89	16			do	Do.
			362	3		1.95	16			do	Do.
			407	3		2.08	16			do	Do.
			394	3		2.20	16			Antidunes	Do.
	.734	4.3	4.7	120	0.18	.16	48	.409	0.416	[Dunes]	Contracted.
			14			[a] .20		.324		do	Do.
			29			[a] .35		.292		do	Do.
			53			[a] .51		.210		do	Do.
			58	6		.50	14	.214		Dunes	Free.
			74			[a] .55		.189			Contracted.
			105	5		.65	16	.186		Transition	Free.
			113			[a] .75		.117			Contracted.
			120			[a] .73		.183			Do.
			159	4		.87	16	.167		Smooth	Free.
			227	4		1.05	16	.163		[Smooth]	Do.
			252	4		1.15	16	.149		Smooth	
			309	3		1.37	16	.143		Transition	Do.
			368	3		1.62	16			Antidunes	Do.
			405	3		1.72	16			[Antidunes]	Do.
			432	3		1.82	16			do	Do.
			456	3		1.90	16			do	Do.
1.96	.363	11	9.5	10	.45	.35	16	.128	.141	[Dunes]	Contracted.
			16	6		.59	16	.106		Dunes	Free.
		25	26	10	.73	.71	16	.105	.113	do	Contracted.
			40	7		.90	16	.100		Transition	Free.
			60	4		.99	16	.089		do	Do.
			77	4		1.09	16	.080		do	Do.
			90	4		1.21	16	.078		Smooth	Do.
			124	4		1.41	16	.067		do	Do.
			163	4		1.63	16	.063		Transition	Do.
			175	4		1.67	16	.064		do	Do.
			203	4		1.85	16	.067		do	Do.
			227	4		1.93	16	.061		do	Do.
			227	4		2.03	16	.060		do	Do.
	.545		30	8		.56	16	.148		Dunes	Free.
			55	5		.70	16	.127		do	Do.
			79	5		.79	16	.113		do	Do.
			101	6		.92	16	.115		Transition	Do.
			138	5		1.07	16	.100		Smooth	Do.
			165	4		1.10	16	.098		do	Do.
			210	4		1.34	16	.094		Transition	Do.
			241	4		1.38	16	.094		do	Do.
			266	4		1.58	16	.080		do	Do.
			321	3		1.85	16	.071		Antidunes	Do.
			331	3		1.85	16			do	Do.
			355	3		1.96	16			do	Do.
			386	3		2.06	16			[Antidunes]	Do.
	.734	36	32	8	.42	.45	16	.205	.195	[Dunes]	Contracted.
		34	41	10	.54	.41	18	.194	.209	Dunes	Do.
			49	5		.37	16	.177		do	Free.
			55	5		.49	12	.171		do	Do.
		70	63	6	.53	.60	16	.149	.161	[Dunes]	Contracted.
		68	73	7	.46	.58	16	.165	.175	Dunes	Do.
			72	5		.61	16	.155		do	Free.
			87	4		.60	16	.155		Transition	Do.
		121	101	6	.67	.70	16	.120	.145	do	Do.
			96	5		.75	16	.147		Dunes	Do.
			166	3		.92	14	.139		Transition	Do.
			241	4		1.17	16	.117		Smooth	Do.
			259	4		1.22	16	.113		[Smooth]	Do.
			302	3		1.31	16	.106		Transition	Do.
			334	3		1.53	16	.105		Antidunes	Do.
			350	3		1.49	14			[Antidunes]	Do.
			362	3		1.45	16			do	Do.
			368	3		1.50	16			do	Do.
	1.119		90	5		.53	16	.222		Dunes	Free.
		117	112	6	.68	.61	16	.188	.205		Contracted.
		130	131	4	.60	.64	16	.184	.202	Smooth	Do.
		133	138	6	.65	.56	16	.180	.180	do	Do.
			140	5		.65	16	.196			Free.
		129	149	5	.79	.69	16	.186	.199	Smooth	Do.
		132	158	4	.79	.71	16	.189	.192	do	Do.
			215	5		.78	16	.178		do	Do.
			253	3		.78	16	.171		do	Do.
			331	3		.97	16	.166		do	Do.
			340	3		1.03	16	.152		do	Do.
			397	3		1.12	16			Transition	Do.

[a] Computed graphically from data in a notebook afterward lost.

Table 4 (D).—*Observations on load, slope, and depth, with débris having 1,460 particles to the gram, or grade (D).*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.66	0.093		5.3	6		0.80	16	0.077		Dunes	Free.
			8.1	6		.94	16	.077		do	Do.
			13	5		1.19	16	.075		Transition	Do.
			20	4		1.39	16	.076		do	Do.
			21	5		1.68	16	.063		Smooth	Do.
			29	4		1.83	16	.058		do	Do.
			36	6		1.88	16	.061		do	Do.
			45	4		1.98	16	.063		do	Do.
			47	4		2.25	16	.056		do	Do.
			62	4		2.47	16	.056		do	Do.
	.182	6.4	5.8	7		.39	16	.166		Dunes	Contracted.
			14	6		.77	16	.147		do	Free.
			17	6		.82	16	.135		do	Do.
			23	6		.95	16	.123		Transition	Do.
			30	5		1.10	16	.105		do	Do.
			47	4		1.26	16	.108		Smooth	Do.
			53	4		1.40	16	.108		do	Do.
			83	8		1.95	16	.090		do	Do.
			108	9		2.10	16	.090		do	Do
			121	4		2.26	16	090		do	Do.
			127	4		2.28	16	.093		do	Do.
			134	4		2.39	16	.090		do	Do.
	.545	8.9	6.9	6	.30	.19	16	.460	0.464	Dunes	Contracted.
		8.9	9.5	5	.28	.20	16	.422	.425	[Dunes]	Do.
		18	17	5	.61	.51	14	.403	.382	Dunes	Do.
		32	27	5	.61	.57	16	.318	.322		Do.
		33	37	4		.64	16	.316			Do.
			64	5		.81	12	.267		Transition	Free.
			92	4		.96	16	.237		Smooth	Do.
			145	4		1.25	16	217		do	Do
			172	4		1.42	16	.211		do	Do.
			203	4		1.55	12	.202		do	Do.
			209	4		1.58	12	.209		do	Do.
			218	3		1.57	12	.191		do	Do.
			231	3		1.65	14	.177		do	Do.
			331	3		1.98	12	.196		do	Do.
			310	3		2.02	12			Transition	Do.
1.00	.182		9.5	7		.69	14	.110		Dunes	Free.
			16	5		.84	16	.100		do	Do.
			22	5		1.06	14	.094		Transition	Do.
			27	5		1.08	16	.099		do	Do.
			28	4		1.14	16	.088		do	Do.
			48	4		1.34	16	.086		do	Do.
			49	4		1.39	16	.082		Smooth	Do
			56	4		1.57	16	.071		do	Do
			80	4		1.83	16	.066		do	Do
			98	4		2.09	16	.070		do	Do
			109	4		2.33	14	.066		do	Do
			126	4		2.55	14	.062		do	Do
			152	3		2.75	16	.064		do	Do
	.363	0	0		.037		40	.418		Dunes	Contracted.
		1.8	2.3	81	.16	.18	28	.292	.289	[Dunes]	Do.
		1.8	2.0	66	.19	.18	24	.283	.286	do	Do.
		5.9	5.4	20	32	.25	24	.245	.252	Dunes	Do.
		12	12	22	.27	.35	20	.224	.224	[Dunes]	Do.
		12	12	26	.56	.43	20	.235	.229	do	Do.
		23	23	12	.53	.58	24	.209	.199	do	Do.
			28	6		.65	16	.170		Dunes	Free.
			35	5		.80	16	.164		Transition	Do.
			86	4		1.14	16	.136		Smooth	Do.
			112	4		1.32	16	.120		do	Do.
			130	4		1.44	14	.116		do	Do.
			141	3		1.49	16	.117		do	Do.
			170	3		1.65	14	.115		do	Do.
			181	4		1.75	16	.103		do	Do.
			229	4	1.85	1.94	14	.104	.099	do	Do.
			258	3	2.00	2.11	14	.101	.098	do	Do.
	.545	30	30	4	.53	.53	16	.236	.240		Contracted.
		32	31	4		.55	16	.241			Do.
			66	4		.78	16	.187		Transition	Free.
			143	4		1.11	16	.166		Smooth	Do.
			168	4		1.26	16	.162		do	Do.
			229	4		1.58	16	.136		do	Do.
			256	3		1.61	16	.136		do	Do.
			281	3		1.62	14	.140		do	Do.
			310	3		1.74	14	.136		do	Do.
			340	3		1.91	14	.136		do	Do.

TABLE 4 (D).—*Observations on load, slope, and depth, with débris having 1,460 particles to the gram, or grade (D)*—Con.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.00	0.734	0	0	....	0.085	....	40	....	....	Dunes forming..........	Contracted.
		5.8	6.5	29	.18	0.21	36	0.491	0.482	[Dunes]..........	Do.
		19	12	18	.22	.32	24	.423	411	.....do..........	Do.
		20	21	15	.26	.37	36	.413	.410	.....do..........	Do.
		49	56	4	....	.61	16	.285	....	.....do..........	Do.
		....	66	4	....	.61	12	.250	....	Dunes..........	Free.
		83	82	3	....	.75	16	.241	....	Smooth..........	Contracted.
		....	108	4	....	.83	14	.220	....	Transition..........	Free.
		....	170	3	....	.98	14	.206	....	Smooth..........	Do.
		....	189	4	....	1.09	16	.198	....	.....do..........	Do.
		....	193	4	....	1.19	16	.195	....	.....do..........	Do.
		....	265	3	....	1.39	16	.189	....	.....do..........	Do.
		....	293	3	....	1.46	16	.185	....	.....do..........	Do.
		....	354	3	....	1.73	16	.175	....	.....do..........	Do.
		....	377	3	....	1.76	14	.162	....	.....do..........	Do.
1.32	.363	8.9	11	10	.50	.30	16	.137	.140	[Dunes]..........	Contracted.
		10	11	10	.40	.34	16	.171	.171	.....do..........	Do.
		25	23	8	.46	.67	16	.137	.154	Dunes..........	Do.
		59	53	5	....	1.00	16	.124	....	[Dunes]..........	Do.
		60	57	2	....	1.05	16	.129	....	Dunes..........	Do.
		100	89	4	....	1.25	16	.107	....	....	Free.
		102	97	3	....	1.25	16	.111	....	Smooth..........	Do.
		154	135	3	....	1.54	16	.090	....	.....do..........	Do.
		166	136	3	....	1.57	14	.094	....	[Smooth]..........	Do.
		169	161	3	....	1.67	14	.089	....	Smooth..........	Do.
		195	236	3	....	1.89	16	.088	....	.....do..........	Do.
		202	247	3	....	1.91	16	.087	....	.....do..........	Do.
	.734	17	15	10	.28	.34	16	.360	.354	Dunes..........	Contracted.
		22	25	10	.33	.37	16	.272	.304	.....do..........	Do.
		48	43	10	.60	.52	14	.243	.227	[Dunes]..........	Do.
		50	49	8	.51	.58	16	.224	.248	.....do..........	Do.
		53	47	8	.64	.61	16	.233	.231	Dunes..........	Do.
		51	60	5	....	.62	14	.202	....	....	Do.
		65	72	5	....	.55	16	.201	....	....	Do.
		68	59	5	.75	.70	16	.206	.228	....	Do.
		86	72	5	.66	.79	16	.184	.192	....	Do.
		90	83	5	....	.67	16	.181	....	....	Do.
		99	84	4	1.28	1.15	16	....	....	[Smooth]..........	Do.
		172	170	3	1.00	1.00	12	.154	.164	Smooth..........	Do.
		202	174	3	.97	.98	14	.160	.168	.....do..........	Do.
		192	209	3	....	1.15	12	.156	....	.....do..........	Do.
		192	200	3	....	1.17	12	.152	....	.....do..........	Do.

TABLE 4 E1. — *Observations on load, slope, and depth, with débris having 142 particles to the gram, or grade (E).*

Width.	Discharge.	Load.		Period.	Slope.		Depth.			Character of bed.	Outfall.
		Feed.	Collection.		Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.66	0.182	25	21	15		1.20	16	0.125		Dunes	Contracted.
		25	21	19		1.27	16	.117			Do.
		31	28	15		1.43	16	.115		Transition	Do.
		31	31	13		1.48	16	.115			Do.
		31	30	15		1.56	16	.114			Do.
	.363	38	31	9		1.04	16	.200		Transition (dunes to smooth).	Contracted.
		38	31	8		1.04	16				Do.
		48	42	9		1.27	16	.197		Transition	Do.
		48	46	10		1.26	16	.200			Do.
		48	47	10		1.29	16	.185			
	.734	48	47	6		1.03	16	.372		Dunes	Contracted.
		48	50	6		1.09	16	.387		do	Do.
		96	95	1		1.43	16			do	Do.
		96	97	4		1.46	16			do	Do.
	1.119	50	44	6		.56	14	.562		Dunes	Contracted.
		91	80	3		1.23	16			[Dunes]	Do.
		91	85	3		1.31	16			do	Do.
		101	94	3		1.11	16			Dunes	Do.
		101	87	3		1.24	16			[Dunes]	Do.
		101	94	3		1.31	16			do	Do.
		101	95	3		1.29	16			do	Do.
		193	167	3		1.38	16			do	Do.
		193	184	3		1.28	16			Dunes	Do.
		193	186	3		1.41	16				Do.
1.00	.182	6.4	5.2	21		.59	16			Dunes	Contracted.(?)
		19	19	10		1.11	16	.094			Do.
		19	19	16		1.12	16	.087			Do.
		47	44	8		1.80	16	.081			Do.
		50	44	8		1.80	16	.077			Do.
		50	50	9		1.94	16	.093			Do.
		78	75	5		2.42	16				Do.
	.363				0.065		32	.357			Contracted.
			Tr.		.11		32	.314		Dunes forming	Do.
		2.1	2.9	61	.23	.22	48	.241	0.277	[Dunes]	Do.
		2.1	2.2	60		.25	48	.242		Dunes	Do.
		6.7	7.7	20	.46	.44	48	.218	.215		Do.
		6.6	7.9	20	.39	.44	32	.212	.208		Do.
		24	22	34	.80	.87	16	.161	.167	Transition	Free.
		50	53	9	1.24	1.28	16			do	Contracted.
		95	104	5	1.92	1.83	16	.113		do	Do.
		142	168	4	2.26	2.29	16	.110	.115	do	Do.
	.734				.04		32	.618		[Dunes]	Contracted.
			Tr.		.07		32	.562		do	Do.
		2.1	1.7	70		.19	48	.447		do	Do.
		2.1	3.6	63	.17	.18	48	.442	.459	do	Do.
		6.9	4.5	31	.31	.29	32	.411	.403	do	Do.
		6.9	10	25	.31	.26	40	.403	.407	do	Do.
		21	20	8	.43	.46	28	.364	.363	do	Do.
		21	20	18		.48	16	.303		do	Do.
		24	26	16	.61	.47	16	.301		Dunes	Do.
		41	44	10		.73	30	.324		[Dunes]	Do.
		41	47	6		.74	36	.326		do	Do.
		47	45	8	.82	.83	16	.273		Dunes	Do.
		87	86	6		1.19	16	.236		Transition	Do.
		95	100	4	1.17	1.23	16	.223			Do.
		142	135	3	1.50	1.46	16	.187			Do.
		142	150	3	1.47	1.50	16	.189			Do.
		203	220	2	1.80	1.61	16			Smooth	Do.
	1.119	47	50	6		.52	16	.380			Contracted.
		47	50	8		.59	16	.406			Do.
		189	170	3		1.15	16				Do.
		189	190	3		1.18	16				Do.
1.32	.363	20	20	15		.67	16	.131		Dunes	Contracted.
		20	20	10		.73	16	.129		do	Do.
		86	93	5		1.78	16	.097			Do.
	.734	33	33	9		.60	16	.239		Dunes	Contracted.
		86	85	4		1.10	16	.198			Do.
		86	86	3		1.12	16	.211			Do.
	1.119	50	46	6		.58	16	.324		Dunes	Contracted.
		50	50	4		.62	16	.317		do	Do.
		172	163	3		1.13	16				
		172	171	3		1.22	16				

TABLE 4 (F).—*Observations on load, slope, and depth, with débris having 22.1 particles to the gram, or grade (F).*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.66	0.182	11	11	17	...	1.29	16	0.118	...	Smooth	Contracted.
		11	12	23	...	1.31	16	.129	...	[Smooth]	Do.
		58	52	11	...	2.51	16	.102	...	Smooth	Do.
		58	53	8	...	2.50	16	.106	...	do	Do.
	.363	26	26	17	...	1.12	16	.207	...	Smooth	Contracted.
		26	26	12	...	1.13	16	.204	...	do	Do.
		71	80	6	...	1.89	16	.176	...	...	Do.
		71	71	10	...	1.96	16	.170	...	...	Do.
	.734	35	37	9	...	.97	16	.346	...	Dunes	Contracted.
		35	38	6	...	1.00	16	.340	...	[Dunes]	Do.
		106	103	3	...	1.68	16	...	...	Dunes	Do.
		106	108	3	...	1.75	16	...	...	do	Do.
1.00	.182	6.8	6.8	21	...	1.36	16	.090	...	Smooth	Free. (?)
		41	42	7	...	2.49	16	.078	...	do	Do.
		41	44	7	...	2.53	16	.080	...	do	Do.
	.363	10	9.5	18	...	.85	16	.160	...	Smooth	Free. (?)
		10	10	20	...	.91	16	.161	...	do	Do.
		51	47	14	...	1.65	16	.128	...	[Smooth]	Do.
		51	51	10	...	1.70	16	.130	...	do	Do.
		51	56	8	...	1.68	16	.140	...	Smooth	Do.
		120	120	3	...	2.47	16	...	...	...	Do.
	.734	26	25	14	...	.77	16	.268	...	Dunes	Contracted.
		26	25	12	...	.77	16	.265	...	do	Do.
		104	98	5	...	1.52	16	.217	...	do	Do.
		104	114	5	...	1.60	16	.211	...	do	Do.
	1.119	52	53	5	...	.80	16	.330	...	Dunes	Free. (?)
		52	56	5	...	.85	16	.343	...	do	Do.
		207	197	3	...	1.65	16	...	...	do	Do.
		207	209	3	...	1.67	16	...	...	do	Do.
1.32	.363	21	21	7	...	1.16	16	.116	...	Smooth	Contracted.
		21	21	21	...	1.21	16	.118	...	do	Do.
		70	68	9	...	2.05	16	.114	...	Transition	Do.
		70	72	5	...	2.07	16	.108	...	do	Do.
	.734	26	26	13	...	.83	16	.212	...	Dunes	Contracted.
		26	27	12	...	.85	16	.209	...	do	Do.
		26	27	12	...	.86	16	.215	...	[Dunes]	Do.
		104	102	3	...	1.48	16	.176	...	...	Do.
		104	106	4	...	1.58	16	.180	...	...	Do.
	1.119	58	50	12	...	.74	16	.275	...	Dunes	Contracted.
		58	50	9	...	.78	16	.288	...	do	Do.
		58	59	6	...	.84	16	.284	...	do	Do.
		212	188	2	...	1.55	16	...	...	[Dunes]	Do.
		212	208	2	...	1.60	16	...	...	Dunes	Do.

TABLE 4 (G).—*Observations on load, slope, and depth, with débris having 5.9 particles to the gram, or grade (G).*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.66	0.363	10	11	15	...	1.11	16	0.198	...	...	Contracted.
		25	25	12	...	1.44	16	.186	...	...	Do.
		25	28	15	...	1.48	16	.192	...	...	Do.
		51	47	6	...	1.82	16	.175	...	...	Do.
		50	50	8	...	1.90	16	.175	...	...	Do.
		100	100	3	...	2.56	16	.160	...	...	Do.
		100	105	3	...	2.70	16	.158	...	...	Do.
	.734	10	8.5	14	...	.68	16	.373	...	...	Contracted.
		10	11	23	...	.70	16	.364	...	...	Do.
		25	26	11	...	.95	16	.342	...	...	Do.
		50	48	7	...	1.19	16	.322	...	...	Do.
		50	49	11	...	1.19	16	.324	...	...	Do.
		105	104	5	...	1.71	16	.292	...	...	Do.
		203	210	3	...	2.43	16	.261	...	...	Do.
		210	219	3	...	2.35	14	.264	...	...	Do.
	1.119	10	12	18	...	.62	16	.558	...	...	Contracted.
		50	49	6	...	.98	16	.460	...	...	Do.
		50	54	6	...	1.02	16	.451	...	...	Do.
		100	94	4	...	1.35	16	.414	...	...	Do.
		100	114	4	...	1.32	16	.411	...	...	Do.
		203	212	3	...	1.97	16	.374	...	...	Do.
		203	215	3	...	1.95	16	.378	...	...	Do.
		304	311	3	...	2.40	16	.354	...	...	Do.
		304	331	3	...	2.36	16	...	...	...	Do.

TABLE 4 (G).—*Observations on load, slope, and depth, with débris having 5.9 particles to the gram, or grade (G)*—Con.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.00	0.363	10	10	20		1.27	16	0.143		Smooth	Contracted.
		20	21	15		1.48	16	.139		[Smooth]	Do.
		25	25	12		1.61	16	.136		Smooth	Do.
		25	28	18		1.62	16	.141		do	Do.
		34	34	12		1.76	16	.132		do	Do.
		51	50	9		2.09	16	.129		do	Do.
		102	97	5		2.74	16	.114			Do.
	.734	10	11	42		.78	16	.272		Smooth	Contracted.
		20	20	15		.86	16	.248		[Smooth]	Do.
		25	25	15		.95	16	.248		do	Do.
		25	26	11		.97	16	.251		Smooth	Do.
		50	49	10		1.27	16	.235		[Smooth]	Do.
		101	100	5		1.69	16	.214		Smooth	Do.
		201	189	4		2.30	16	.190			Do.
		201	212	3		2.37	16	.191			Do.
	1.119	10	10	20		.64	16	.389		Smooth	Contracted.
		25	24	15		.66	16	.357			Do.
		25	25	17		.67	16	.359			Do.
		50	53	6		.97	16	.324			Do.
		50	54	7		.90	16	.326			Do.
		101	100	4		1.22	16	.308			Do.
		102	103	4		1.31	16	.307			Do.
		204	214	3		1.78	16	.275			Do.
		306	297	3		2.04	14	.252			Do.
		306	310	3		2.21	14	.253			Do.
1.32	.363	25	24	12		1.90	16	.115			Contracted.
		25	26	9		1.97	16	.104			Do.
		51	49	10		2.25	16	.108			Do.
		51	47	10		2.34	16	.105			Do.
		98	95	3		3.02	16	.093			Do.
		98	123	4		3.10	16	.097			Do.
	.734	10	9	21		.82	16	.210			Contracted.
		10	12	18		.82	16	.210			Do.
		25	24	13		1.08	16	.194			Do.
		25	27	13		1.14	16	.200			Do.
		51	52	6		1.41	16	.193			Do.
		102	102	4		1.82	16	.171			Do.
		203	200	3		2.44	16	.163			Do.
	1.119	10	14	19		.71	16	.297			Contracted.
		51	46	4		.90	16	.270			Do.
		51	67	6		1.07	16	.261			Do.
		98	95	3		1.31	16	.248			Do.
		98	110	4		1.40	16	.245			Do.
		197	200	3		1.83	16	.230			Do.
		295	282	3		2.17	16	.201			Do.
		304	302	3		2.26	16	.202			Do.

TABLE 4 (H).—*Observations on load, slope, and depth, with débris having 2.0 particles to the gram, or grade (H).*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
0.66	0.363	10	9.2	21		1.49	16	0.184			Contracted.
		10	12	16		1.58	16	.184			Do.
		21	17	18		1.80	16	.183			Do.
		21	22	14		1.84	16	.173			Do.
		52	51	5		2.43	16	.167			
		52	56	6		2.47	16	.173			
	.734	10	7.9	18		.90	16	.345			Contracted.
		10	11	17		.95	16	.348			Do.
		21	20	17		1.10	16	.333			Do.
		21	22	15		1.19	16	.344			Do.
		52	51	8		1.50	16	.320			Do.
		52	52	8		1.51	16	.310			Do.
		105	105	4		2.02	16	.289			Do.
		209	209	3		2.69	16	.250			Do.
		209	222	3		2.92	16	.253			Do.
	1.119	10	12	16		.74	16	.502			Contracted.
		10	10	20		.81	16	.510			Do.
		10	12	21		.89	16	.503			Do.
		26	26	15		1.03	16	.470			Do.
		52	53	13		1.26	16	.442			Do.
		52	54	10		1.28	16	.437			Do.
		52	53	9		1.33	16	.447			Do.
		105	98	3		1.65	14	.391			Do.
		105	106	6		1.63	16	.398			Do.
		105	113	3		1.62	16	.392			Do.
		209	209	3		2.31	16	.340			Do.
		209	209	3		2.38	16	.334			Do.

TABLE 4 (I).—*Special group of observations on load, slope, and depth, with débris of grade C; for discussion of form ratio.*

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.00	0.734	74	84	4		0.58	16	0.232		Transition	Contracted.
		76	45	4		.58	14	.241		do	Do.
		160	194	3		.99	16	.194			Do.
	.923	96	103	3		.58	16	.270		Transition	Contracted.
		94	103	3		.62	16	.282		do	Do.
		254	280	2		1.09	16	.233			Do.
	1.119	111	118	3		.57	14	.312		Transition	Contracted.
		114	129	3		.66	14	.305			Do.
1.20	.734	66	74	3		.51	16	.222		Transition	Contracted.
		67	74	3		.60	16	.215		[Transition]	Do.
		193	218	3		1.05	16	.173		Transition	Do.
		199	223	3		1.07	16	.175		[Transition]	Do.
	.923	99	104	3		.65	14	.232		Transition	Contracted.
		249	266	3		1.06	16	.210		do	Do.
		246	274	3		1.01	16	.201		do	Do.
	1.021	105	107	3		.57	16	.250		[Transition]	Contracted.
		110	109	4		.54	16	.262		Transition	Do.
		304	325	3		1.20	16	.197		Smooth	Do.
	1.119	108	114	4	0.56	.62	12	.269	.277	[Transition]	Contracted.
		111	123	4		.61	16	.269		Transition	Do.
		322	292	3		1.00	16	.224		[Smooth]	Do.
		339	326	3		1.03	14	.231		Smooth	Do.
1.40	.734	76	74	4		.63	16	.199		Transition	Contracted.
		76	75	4		.59	14	.196		do	Do.
		220	215	3		1.04	16	.158		Smooth	Do.
		216	226	3		1.07	16	.151		do	Do.
	.923	72	79	4		.51	16	.235		[Transition]	Contracted.
		82	74	4		.57	16	.237		Transition	Do.
		271	279	3		1.03	16	.176		Smooth	Do.
		283	297	3		1.04	14	.175		[Smooth]	Do.
	1.021	82	97	4		.58	16	.248			Contracted.
		292	319	3		1.03	14	.181		[Smooth]	Do.
		289	323	3		1.08	16	.180		Smooth	Do.
	1.119	105	104	4		.57	16	.254			Contracted.
		123	130	4		.61	16	.231			Do.
		292	325	3		.97	14	.213		Smooth	Do.
		284	337	3		1.01	14	.215		[Smooth]	Do.
		292	312	3		1.07	16	.203		Smooth	Do.
1.60	.734	69	70	4		.60	12	.191			Contracted.
		265	236	3		1.14	16	.121		Smooth	Do.
		269	268	3		1.12	16	.122		do	Do.
	.923	67	82	4		.45	12	.233		Dunes	Contracted.
		69	69	5		.46	12	.202		do	Do.
		67	66	4		.50	12	.224		[Dunes]	Do.
		298	299	3		1.05	16	.161		Smooth	Do.
		289	280	3		1.07	16	.161		do	Do.
	1.021	67	66	4		.39	12	.243			Contracted.
		63	73	4		.47	12	.244			Do.
		66	80	4		.51	12	.232			Do.
		310	311	3		1.06	16	.169			Do.
	1.119	82	83	4		.49	16	.227		Transition	Contracted.
		96	91	4		.47	12	.234		[Transition]	Do.
		85	98	4		.55	12	.233		do	Do.
		336	332	3		.99	12	.188			Do.
1.80	.734	69	69	4		.61	16	.174		Dunes	Contracted.
		70	72	4		.60	16	.174		do	Do.
		211	204	3		1.04	16	.137		Smooth	Do.
		205	203	3		1.06	16	.130		do	Do.
	.923	70	75	4		.53	14	.206		Dunes	Contracted.
		67	74	4		.58	14	.204		do	Do.
		260	258	3		1.04	16	.157		[Smooth]	Do.
		260	273	3		1.04	16	.152		Smooth	Do.
	1.021	70	69	4		.51	16	.224		Dunes	Contracted.
		69	76	4		.52	14	.227		[Dunes]	Do.
		70	76	4		.57	16	.225		Dunes	Do.
		292	323	3		1.00	14	.155		Smooth	Do.
		296	308	3		1.01	16	.158		do	Do.
	1.119	64	66	4		.42	14	.240		Dunes	Contracted.
		75	74	4		.47	14	.243		do	Do.
		386	375	3		1.05	16	.160		Smooth	Do.
		363	385	3		1.05	12	.167		do	Do.

TABLE 4 (I).—*Special group of observations on load, slope, and depth, with débris of grade (C)*—Continued.

Width.	Discharge.	Load.			Slope.			Depth.		Character of bed.	Outfall.
		Feed.	Collection.	Period.	Water surface.	Bed.	Distance.	By gage.	By profiles.		
Feet.	*Ft.³/sec*	*Gm./sec*	*Gm./sec.*	*Minutes.*	*Per cent.*	*Per cent.*	*Feet.*	*Feet.*	*Feet.*		
1.96	0.734	85	83	4	....	0.61	16	0.147	....	[Transition]	Contracted.
		84	88	4	....	.69	16	.146	....	Transition	Do.
		234	236	3	....	1.05	16	.117	....	Smooth	Do.
		222	231	3	....	1.09	16	.123	....	.....do	Do.
		234	250	3	....	1.12	16	.122	....	....	Do.
	.923	96	97	3	....	.62	16	.176	....	Transition	Contracted.
		246	279	3	....	1.02	16	.143	....	....	Do.
	1.021	84	85	4	....	.50	16	.194	....	[Transition]	Contracted.
		85	87	4	....	.57	14	.200	....	Transition	Do.
		94	104	3	....	.54	16	.193	....	[Transition]	Do.
		328	343	3	....	1.09	16	.141	....	.....do	Do.
		316	352	3	....	1.09	16	.144	....	Transition	Do.
	1.119	82	82	4	....	.45	12	.214	....	Dunes	Contracted.
		85	84	4	....	.57	16	.222	....	Transition	Do.
		82	94	4	....	.52	16	.219	....	.....do	Do.
		345	341	3	....	1.00	16	.150	....	Smooth	Do.
		328	3[illegible]3	3	....	1.00	16	.147	....	[Smooth]	Do.

TABLE 4 (J).—*Observations on load, slope, and depth, with débris of two or more grades mixed.*

Designation of mixture, component grades, and percentages by weight.	Width of trough.	Discharge.	Load.			Slope of bed.		Depth by gage.	Character of bed.
			Feed.	Collection.	Period.	Per cent.	Distance.		
	Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*		*Feet.*	*Feet.*	
(A_1C_1)–(A)50 : (C)50	1.00	0.363	42	43	8	0.58	16	....	Transition.
			90	91	4	.92	16	....	Do.
			128	140	4	1.23	16	....	Antidunes.
			171	169	3	1.47	16	....	Do.
(A_3G_1)=(A)75 : (G)25	1.00	.363	20	18	12	.51	16	....	Smooth.
			90	74	5	.93	16	....	Transition.
			80	89	4	.95	16	....	Do.
			175	164	3	1.38	16	....	Antidunes.
			175	176	3	1.36	16	....	Do.
(A_2G_1)–(A)67 : (G)33	1.00	.363	20	20	12	.53	16	....	Smooth.
			42	42	6	.62	16	....	Do.
			42	42	6	.64	16	....	Do.
			87	88	3	1.00	16	....	Antidunes.
			110	119	3	1.18	16	....	Do.
(A_1G_1)=(A)50 : (G)50	1.00	.363	22	22	8	.68	16	....	Smooth.
			46	43	6	1.01	16	....	Transition.
			91	93	4	1.42	16	....	Do.
(A_1G_2)–(A)33 : (G)67	1.00	.363	42	40	6	1.36	16	....	Smooth.
(A_1G_4)=(A)22 : (G)78	1.00	.363	22	21	20	1.30	16	....	
			43	42	7	1.79	16	....	
(B_4F_1)=(B)78 : (F)22	1.00	.363	42	43	6	.59	16	....	Smooth.
			84	92	3	.86	16	....	Do.
			113	105	3	.99	16	....	Do.
			113	125	3	1.05	16	....	Do.
			169	159	2	1.38	16	....	Transition.
(B_2F_1)=(B)64 : (F)36	1.00	.363	39	42	7	.57	16	....	Smooth.
			78	80	5	.85	16	....	Do.
			105	109	4	1.11	16	....	Do.
			157	157	2	1.49	16	....	Do.
(B_1F_1)=(B)47 : (F)53	1.00	.363	45	49	7	.73	16	....	Transition.
			90	95	4	1.14	16	....	Do.
			120	130	3	1.41	16	....	Smooth.
			181	162	2	1.61	16	....	Do.
(B_1F_2)=(B)31 : (F)69	1.00	.363	28	35	11	.86	16	....	Dunes.
			41	40	6	1.06	16	....	Do.
			81	82	4	1.56	16	....	Do.
(B_1F_4)=(B)18 : (F)82	1.00	.363	16	17	15	.82	16	....	Dunes.
			27	29	10	1.16	14	....	Do.
			40	43	6	1.46	16	....	Do.
(C_4E_1)=(C)79 : (E)21	1.00	.363	43	49	8	.70	16	....	Smooth.
			85	84	4	.93	16	....	Do.
			115	118	3	1.15	16	....	Do.
			171	171	2	1.52	16	....	Do.

TABLE 4 (J).—*Observations on load, slope, and depth, with débris of two or more grades mixed*—Continued.

Designation of mixture, component grades, and percentages by weight.	Width of trough.	Discharge.	Load.			Slope of bed.		Depth by gage.	Character of bed.
			Feed.	Collection.	Period.	Per cent.	Distance.		
	Feet.	*Ft.³ sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*		*Feet.*	*Feet.*	
(C_2E_1)=(C)65 : (E)35	1.00	0.182	78	81	3	1.77	16	....	Smooth.
			104	105	4	2.06	16	....	Do.
		.363	43	42	7	.69	16	....	Transition.
			85	85	4	1.03	16	....	Do.
			114	117	3	1.27	16	....	Smooth.
			155	170	3	1.57	16	....	Do.
			171	169	3	1.65	16	....	Do.
			155	170	4	1.60	16	....	Do.
			171	173	3	1.74	16	....	Do.
(C_1E_1)=(C)48 : (E)52	1.00	.182	26	28	12	.99	16	0.096	Transition.
			40	40	10	1.17	16	.090	Do.
			40	41	10	1.27	16	.091	Do.
			53	50	6	1.43	16	.081	Smooth.
			51	60	....	1.50	16	....	Do.
			53	52	6	1.51	16	.082	Do.
			51	61	....	1.55	16	....	Do.
			81	67	4	1.82	16	....	Do.
			77	78	....	1.95	16	....	Do.
			81	87	5	1.89	16	....	Do.
		.363	39	40	6	.74	16	.150	Transition.
			39	41	7	.76	16	.151	Do.
			78	78	5	1.07	16	....	Smooth.
			104	93	3	1.37	16	....	Do.
			104	115	3	1.40	16	....	Do.
			104	119	3	1.43	16	....	Do.
			157	158	3	1.85	16	....	Do.
(C_1E_2)=(C)31 : (E)69	1.00	.182	26	26	10	1.10	16	.093	Transition.
			39	39	8	1.37	16	.088	Do.
			52	57	6	1.64	16	.082	Smooth.
			78	76	3	2.22	16	....	Do.
		.363	39	39	8	.77	16	....	Dunes.
			39	39	9	.84	16	....	Do.
			78	81	3	1.25	16	....	Do.
			108	112	3	1.54	16	....	Transition.
			157	158	3	2.10	16	....	Do.
(C_1E_4)=(C)19 : (E)81	1.00	.182	20	20	14	1.02	16	....	Dunes.
			26	28	10	1.29	16	.085	Do.
			39	40	6	1.61	16	.079	Do.
			39	42	6	1.65	16	.084	Do.
			52	51	6	1.88	16	.078	Transition.
			52	54	12	1.93	16	.082	Do.
		.363	40	40	8	1.00	16	....	Dunes.
			53	56	7	1.14	16	....	Do.
			78	76	4	1.45	16	....	Transition.
			109	109	3	1.75	16	....	Do.
(C_4G_1)=(C)80 : (G)20	1.00	.363	31	32	11	.62	16	....	Dunes.
			93	92	5	1.07	16	....	Transition.
			140	140	4	1.30	16	....	Do.
			187	194	3	1.48	16	....	Smooth.
			187	195	3	1.62	16	....	Do.
(C_2G_1)=(C)67 : (G)33	1.00	.363	31	29	....	.59	16	....	Smooth.
			31	29	12	.63	16	....	Do.
			31	31	10	.62	16	....	Do.
			61	66	7	.90	16	....	Do.
			92	90	4	1.03	16	....	Do.
			92	95	5	1.08	16	....	Do.
			122	120	3	1.20	16	....	Do.
			183	180	2	1.65	16	....	Do.
(C_1G_1)=(C)50 : (G)50	1.00	.363	17	18	15	.71	16	....	Smooth.
			50	50	10	.99	16	....	Do.
			100	105	3	1.34	16	....	Do.
			133	128	3	1.62	16	....	Do.
			133	145	3	1.66	16	....	Do.
(C_1G_2)=(C)33 : (G)67	1.00	.363	16	15	16	.95	16	....	Transition.
			32	34	10	1.17	16	....	Smooth
			32	36	10	1.27	16	....	Do.
			64	69	7	1.59	16	....	Transition.
(E_4G_1)=(E)80 : (G)20	1.00	.363	15	17	15	.72	16	....	Transition.
			31	31	10	1.00	16	....	Smooth.
			61	58	8	1.39	16	....	Transition.
(E_2G_1)=(E)67 : (G)33	1.00	.363	16	15	18	.76	16	....	Smooth.
			32	30	11	1.03	16	....	Do.
			63	59	6	1.45	16	....	Transition.
(E_1G_1)=(E)50 : (G)50	1.00	.363	16	18	18	.87	16	....	Smooth.
			31	34	10	1.12	16	....	Do.
			62	60	8	1.60	16	....	Transition.

TABLE 4 (J).—*Observations on load, slope, and depth, with débris of two or more grades mixed*—Continued.

Designation of mixture, component grades, and percentages by weight.	Width of trough.	Discharge.	Load.			Slope of bed.		Depth by gage.	Character of bed.
			Feed.	Collection.	Period.	Per cent.	Distance.		
	Feet.	*Ft.³/sec.*	*Gm./sec.*	*Gm./sec.*	*Minutes.*		*Feet.*	*Feet.*	
(E_1G_2)=(E)33 : (G)67	1.00	0.363	16	15	14	0.95	16	....	Transition.
			23	23	12	1.18	16	....	Smooth.
			30	29	12	1.35	16	....	
			30	32	11	1.33	16	....	
			45	49	7	1.73	16	....	Transition.
			45	54	7	1.74	16	....	Do.
$(A_1C_1G_2)$=(A)25 : (C)25 : (G)50	1.00	.363	16	13	15	.77	16	....	Transition.
			16	17	10	.79	16	....	Do.
			16	14	15	.82	16	....	Smooth.
			32	33	10	.88	16	....	Do.
				88	5	1.32	16	....	Do.
			126	131	4	1.59	16	....	Transition.
			126	151	4	1.67	16	....	Do.
(CDEFG)=(C)45 : (D)35 : (E)12 : (F)6 : (G)2.	1.00	.182	21	25	12	.82	14	....	Dunes.
			42	45	10	1.23	16	....	Transition.
			84	84	5	1.72	16	....	
		.363	67	69	8	.81	16	....	Smooth.
			67	69	6	.85	16	....	Do.
			84	80	5	.91	16	....	Do.
			84	83	5	.93	16	....	Do.
			84	83	5	.95	16	....	Do.
			113	120	5	1.18	16	....	
			113	118	5	1.19	16	....	
			169	172	4	1.53	16	....	
			169	173	4	1.54	16	....	
		.545	84	90	6	.65	16	....	Smooth.
			84	92	5	.67	16	....	Do.
			169	151	3	1.07	16	....	Do.
			169	177	3	1.13	16	....	Do.
			253	228	3	1.40	16	....	Do.
			253	242	3	1.37	16	....	

TABLE 4 (K).—*Observations on load, slope, and depth, with unassorted débris.* [a]

Width.	Discharge.	Load.			Slope of bed.		Depth by gage.	Character of bed.	Outfall.
		Feed.	Collection.	Period.	Per cent.	Distance.			
Feet.	*Ft.³/sec*	*Gm./sec.*	*Gm./sec.*	*Minutes.*		*Feet.*	*Feet.*		
1.00	0.182	19	18	15	0.74	16	....	Dunes	Contracted.
		19	18	15	.79	16	....	.....do	Do.
		38	38	8	1.00	16	....	Smooth	Do.
		75	76	3	1.55	16	....	.....do	Do.
		145	147	2	2.28	16	....	.....do	Do.
	.363	22	20	10	.43	16	0.169	Transition	Contracted.
		22	27	12	.50	16	.176	.....do	Do.
		38	34	6	.59	16	.157	Smooth	Do.
		38	42	6	.67	16	.158	.....do	Do.
		77	74	5	.89	16	....	.....do	Do.
		154	150	3	1.31	16	....	.....do	Do.

[a] The very coarsest particles were removed by passing the sample through a 6-mesh sieve, and the very finest by passing it over a 60-mesh sieve. It retained the equivalents of grades (A), (B), (C), (D), (E), and (F).

CHAPTER II.—ADJUSTMENT OF OBSERVATIONS.

OBSERVATIONS ON CAPACITY AND SLOPE.

THE OBSERVATIONAL SERIES.

Each of the experiments in stream traction involved six quantities—(1) a fineness, or grade of débris, (2) a width of trough, (3) a discharge, (4) a slope, (5) a load, or capacity, and (6) a depth of current. The experiments were arranged in series, for each of which grade, width, and discharge were constant, while within each the magnitudes of slope, capacity, and depth were varied. There will be frequent occasion to mention these secondary units of the experimental work, and whenever the title *series* seems not sufficiently specific they will be called *observational series*. The number of such series recorded in Table 4 is 153.

The factors of grade, width, and discharge, which are related to an individual series as fixed conditions, or constants, do in fact assume the character of variables when series is compared with series; but their modes of determination and combination are not of such character that their numerical values can be checked and adjusted by means of recorded relations.

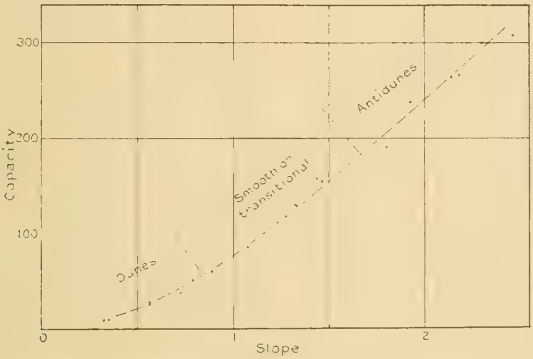

FIGURE 13.—Plot of a single series of observations on capacity and slope. Capacity in grams of débris per second. Slope in per cent. The modes of traction are indicated.

In each experiment the values of slope, load, and depth are mutually dependent; within each series they form a triple progression, the depth decreasing while slope and load increase; but the laws of these interdependent variations are partly masked by irregularities in the sequences. As a preliminary to the general discussion, the observational values were subjected to a process of adjustment, whereby the sequences were freed from irregularities. The irregularities are made manifest by the comparison of the sequences of two variables, and first consideration will be given to those of capacity and slope.

Figure 13 exhibits the relations of capacity to slope as observed in a single series of experiments (that for grade (C), with $w=1.32$ feet and $Q=0.363$ ft.^{3}/sec.). The ordinates indicate capacity, as measured by débris delivered at the lower end of the trough; the abscissas represent slope, as measured on the bed of the channel. The arrangement of the observational dots suggests that if the observations were harmonious the dots would fall in a line of simple curvature. Such a line would express the law connecting capacity and slope. The departures of the dots from such linear arrangement represent irregularities, or errors, in the experimental data. The adjustment proposed is the replacement of the imperfectly alined dots by a generalized or representative line, or the replacement of the inharmonious values of capacity and slope by a system of harmonious or adjusted values.

ERRORS.

As a first step in the treatment of the errors of the data they were studied with a view to the discrimination of the systematic and the accidental.

The three modes of traction—the dune, the smooth, the antidune—although intergrading, are mechanically different. It was surmised that they might differ in efficiency, so that the capacity-slope curve might show a step in passing from one to another; and it was also surmised that the law connecting capacity with slope might not be the same for the several modes. A suggestive observation had shown that on very low slopes—slopes so low that capacity is minute—the current changes an artificially smoothed bed of débris to a system of dunes, and that with the development of dunes the load is notably increased without any change in general slope. To test the surmises all the series were plotted on logarithmic section paper. Figure 14 shows a logarithmic plot of the same data which appear in figure 13; and it will be observed that the line suggested by the points has much less curvature in the logarithmic plot. Its approximation to a straight line makes the study of its local peculiarities comparatively easy. The examination of the plots, while not disproving the surmises, showed that whatever diverse influences may be exerted by the modes of traction, they are too small to be discriminated from the irregularities due to other causes.

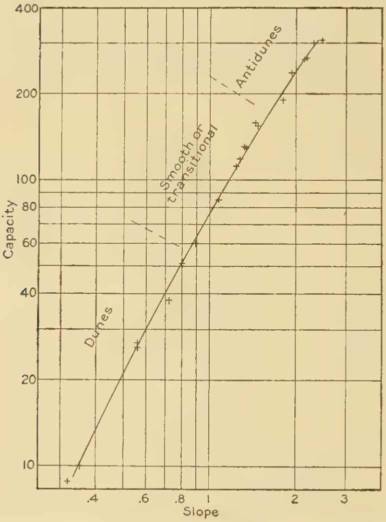

FIGURE 14.—Logarithmic plot of a series of observations on capacity and slope. Compare figure 13.

Other sources of systematic error are connected with the methods of experimentation.

INTAKE INFLUENCES.

As the water entered the experiment trough from the stilling tank it was accelerated, the gain in mean velocity being associated with a quick descent in the surface profile. Beyond this descent the profile usually rose somewhat, and there was commonly a moderate development of fixed waves. This development was modified and the waves were on the whole reduced by the addition of the débris. As it fell into the water the débris had no forward momentum, and it therefore tended to retard the current. But the débris also accumulated on the bottom, reducing the depth of the water at that point, and this reduction necessitated an increase in mean velocity. In the immediate neighborhood of the place where débris was fed the slope of the water was affected by an abnormality distinguishable from the intake abnormality proper, and the joint abnormality faded gradually downstream. The nature of these features varied with the discharge and load, with the gradual development of the adjusted slope, and also with the mode of feeding. During the greater part of the experimental work the feeding was either automatic and continuous or else manipulated by hand in such way as to make it nearly continuous, but for a minor part the feeding was intermittent, a measureful of débris being dumped into the water at regular intervals.

OUTFALL INFLUENCES.

In all the earlier work the trough had the same cross section at the lower end as elsewhere, and the water fell freely from its open end to the settling tank. As the resistance to its forward motion was less at the outfall than within the trough, the water flowed faster there. Its faster flow diminished the resistance just above, and thus the influence of outfall conditions extended indefinitely upstream. An expression of this influence was found in the water profile, which was usually convex in the lower part of the trough, the degree of convexity diminishing upstream. Its effect on the profile of the bed is not readily analyzed, because that profile is adjusted through the velocity of water at the bottom of the current, and the bed velocity is not simply related either to mean velocity or to depth.

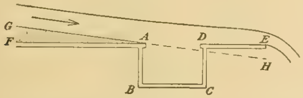

FIGURE 15.—Diagrammatic longitudinal section of outfall end of experiment trough, illustrating influence of sand arrester on water slope.

A second factor at the outfall end was the arrangement for separating the débris from the current. This included a well, *ABCD*, figure 15, which was sunk below the trough bed and into which the débris sank, while the current passed on to the outfall at *E*. In part of the work the space *AD* was entirely open; in another part a coarse screen was stretched across it. In either case the resistance of this part of the channel bed differed from the resistance along the débris slope and may have been greater or less. From the well to the outfall, *DE*, the frictional resistance was less than elsewhere. As the fixed part of the channel bed, *DE*, was horizontal and the débris portion, *GA*, was inclined, the profile of the bed changed at *A*. Projected forward, the slope *GA* passed below *E* to *H*, and when the débris slope, down which the transporting current flowed, was steep, the part *DE* was related to it somewhat as a dam. The tendency of the quasi-dam was to retard the current near the outfall and make the water profile concave, and in some of the experiments the profile actually became concave. Other outfall factors were recognized, but they are not here mentioned because they are believed to be of relatively small importance.

In the reduction of observations on slope an attempt was made to lessen the effect of intake and outfall influences by omitting from the calculations the profile data obtained near the ends of the trough. The data from a considerable number of experiments were finally discarded altogether and do not appear in the tables. To replace the discarded data experiments were afterward made with a modified apparatus.

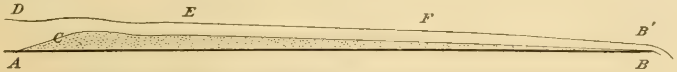

FIGURE 16.—Diagrammatic longitudinal section of débris bed and stream, in a long trough.

CHANGES IN APPARATUS.

As the terminal influences of all kinds diminish with distance from the trough ends, a manifest mode of avoidance is to employ a very long experimental trough and determine slopes from observations in the medial portion exclusively. A trough length of 150 feet was tried and proved moderately successful for very low slopes. For steeper slopes there were practical difficulties—the need either of a trough with adjustable slope or of a very deep trough and a correspondingly large stock of assorted débris—and these led to the consideration of other plans. The one adopted was to contract the channel at the outfall and thus increase the resistance to flow at that point, and with the contracted outfall to use a trough of moderate length. The theory of this plan may be illustrated by a diagram. In figure 16, *AB* represents in profile the bed of a long trough, *CB* the profile of débris, and *DB′* the water profile. In the tract *EF* the water and débris profiles are nearly parallel and depth and velocities are therefore practically uniform. From *F* to *B′* the water profile is notably convex because the resistance to flow afforded by the water itself steadily diminishes toward *B′*.

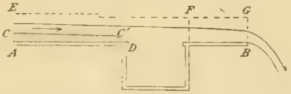

FIGURE 17.—Diagrammatic longitudinal section of outfall end of trough, illustrating influence of contractor.

The plan undertook to introduce at *F*, by contraction, a resistance equivalent to that afforded by the water beyond *F* and then dispense with the portion of the trough between *F* and *B*. In the longitudinal section, figure 17, *ADB* is the bed of the trough, with the well for catching débris, as already shown in figure

15; *EGB* is the profile of one side wall. The walls converge from *F* to *G* (see fig. 3), producing the contraction at the outfall. It was found that the bed of débris, instead of running to a feather edge at *D* (compare fig. 16), held its thickness to *C′* and ended in a steep incline.

The device of contraction accomplished its purpose of avoiding terminal difficulties, but it was found to aggravate certain other difficulties, next to be described.

RHYTHM.

Whenever the profile of a current was determined by a series of measurements applied to the water surface, that surface was found to be in a state of unrest. Its position in any vertical fluctuated upward and downward rhythmically. The amplitude of oscillation, which might be great or small, was not constant: that is, the rhythm was not simple, but compound. It consisted apparently of many rhythmic elements differing one from another in period and amplitude.

The rhythmic quality, thus easily appreciated by watching the play of the surface in relation to a fixed point, permeated every function of the current—the slope of its profile, both local and general, the slope of its bed, the quantity of débris transported, the mode of its transportation. The rhythm of the dune has already been described, but associated with the dunes were greater débris waves, also traveling downstream and each involving the volume of many dunes. In the bed of the long trough a series of them could be seen; in the shorter trough one or two might be made out, or the effect might be only an alternate temporary steepening and flattening of the general slope. The rhythm of the antidune was accompanied by rhythmic paroxysms and doubtless by other rhythms which escaped recognition because the steep slopes with which the antidune was associated were not studied in the long trough. Figure 18 shows a few channel-bed profiles in which rhythmic features appeal to the eye, but the greater number of such profiles merely show an irregularity in which periodicity is not conspicuous. It is probable that the currents were affected by numerous coexistent rhythms, which served to confuse one another and thus masked periodicity except when some one rhythm was stronger than the rest.

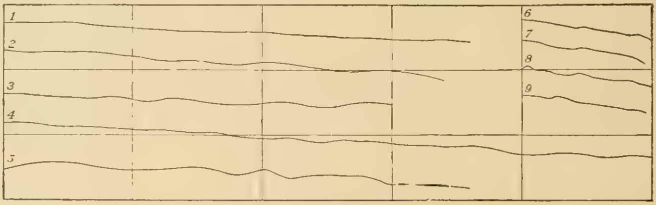

FIGURE 18.—Profiles of channel bed, illustrating tractional rhythms associated with dunes of greater magnitude. Scales: Each horizontal space =20 feet; each vertical space =0.4 foot. For Nos. 1 to 5 the average slope is 0.2 per cent, and the average load (of grade (C)) per foot of channel width is 7 gm./sec. For Nos. 6 to 9 the average slope is 0.6 per cent and the average load 37 gm./sec.

The condition of relatively smooth channel bed which intervened between the conditions characterized severally by dunes and antidunes was also a condition of relative uniformity in all the activities of the current, and when it prevailed the rhythmic variations were at a minimum.

The rhythms of the transporting stream manifestly constitute a group of phenomena worthy of systematic study, but the Berkeley laboratory, having a definite and different theme, treated them only as difficulties interfering with its work. It sought the capacity for load inhering in the average of all the diverse slopes presented by the rhythms, and it necessarily treated the deviations of slope measurements from that average as accidental errors.

The rhythms affected the determinations of loads as well as slopes. The variations of profile were effected by erosion and deposition, and a current which was eroding or depositing carried more load at one point than at another. As the loads were largely determined by weighing the débris delivered at the trough end in a limited time, the amount obtained would depend in part on the phase of slope variation near the point of delivery.

In the earlier experiments with contraction at outfall—as in other experiments it was necessary to continue a run, with uniform discharge and uniform feed of débris, until the slope of the sand bed had been automatically adjusted to the conditions. The criteria adopted for recognition of a state of adjustment were two—that the water slope equal the bed slope and that the rate of delivery of débris equal the rate of feed. It was found impracticable to satisfy these tests, because both slopes and the rate of delivery fluctuated through a wide range, and an approximate adjustment, if attained, could not be made to continue. The state of affairs may be likened to the waving of a flag in the wind; at the outer margin the amplitude of the undulation is much greater than close to the staff. In the long trough the outfall end corresponded to the staff, giving a fixed position and element of uniformity to which the profiles conformed, and the rhythmic departures were greater with distance from the outfall. The shorter trough when combined with end contraction represented a segment of the long trough at a distance from the outfall and was correspondingly subject to great fluctuations. Despite these difficulties, the nature of which was not well understood at the time, a large number of experiments were made in this way.

The work with free outfall was affected chiefly by terminal influences, and as these produced systematic errors there was danger of false conclusions. The work with contracted outfall was affected by accidental errors of such magnitude as largely to mask the nature of the laws sought. Between these perils of Scylla and Charybdis a middle course was finally steered by using a moderate amount of contraction, whereby the recognized systematic errors were practically avoided without the introduction of insuperable rhythmic irregularities.

SLOPES OF DÉBRIS AND WATER SURFACE.

The slope of the bed of débris to which measurement was applied had been established by the stream as that appropriate to the stream's load of débris. It was caused by the load, in conjunction with the discharge and other conditions, and it accurately sufficed to give the stream capacity for that load. This was my point of view in arranging the experimental methods, and accordingly one of the principal measurements undertaken was that of the débris profile. But the slope more generally considered in hydraulic studies is that of the water surface. Head, the hydraulician's ordinary measure for the determination of power, is the vertical interval between two points of the water surface, and slope is the loss of head in a unit of distance. Under conditions of uniform flow the two profiles are parallel, but for various reasons our experimental currents ordinarily lacked so much of uniformity that the two slopes were appreciably different. I do not find it easy to decide which slope should be regarded as the true correlative of capacity for traction, but as all our laboratory data include the débris slope, while the determinations of water slope were relatively infrequent, the discussion of results has adhered almost exclusively to the former. If the water slope is the true correlative, then the use of the débris slope involves a systematic error.

THE LOGARITHMIC PLOTS.

When the data of an observational series are plotted on ordinary section paper, as in figure 13, and a representative line is drawn through or among them, that line is the graphic equivalent of

$$C=f\,(S) \quad \text{--------------} \quad (2)$$

When they are plotted on logarithmic section paper, as in figure 14, and a representative line is drawn, that line is the graphic equivalent of

$$\log C=f_1\,(\log S) \quad \text{------} \quad (3)$$

The second equation, or line, is the logarithmic form of the first.

As already mentioned, a logarithmic plot was made of each observational series. The plot included primarily the slopes of the débris bed and the determinations of load from the delivery of débris at the end of the trough, but it included also, with distinctive notation, such determinations as were available of water-surface slopes and of load based on the rate of feed at the head of the trough. The notation also classified observations with reference to the three modes of traction and distinguished experiments made with use of the contractor from those with free outfall.

A critical study of these plots led to several conclusions. (1) Judged by the internal evidence of regularity and irregularity, the observations of débris slope and water slope have about the same quality. (2) Similarly, the observations of load fed and load delivered have about the same quality. (3) As already stated, the law of sequence is not discovered to change in passing from one process of traction to another; the assumption of a continuous law is the best practicable. (4) Except for very low slopes, the results obtained with the use of the contractor do not differ widely from those without it. (5) There are differences between bodies of experimental data obtained at different stages of the work—differences of uncertain source but presumably connected with modes of manipulation—which make it desirable to treat such bodies separately whenever practicable. (6) The best representative line is not straight but curved, and its curvature is always in one direction.

If the representative line were straight, function (3) would have the form

$$\log C = \log A + n \log S \text{ - - - - - - - - - } (4)$$

in which A is a constant capacity and n a ratio; and function (2) would have the form

$$C = AS^n \text{ - - - - - - - - - - - - - - - } (5)$$

On some of the plots the observational points are too irregular to afford trustworthy evidence of curvature. On most of them the indicated curvature is slight. From inspection of the data during the progress of the experiments it was thought that the true representative line would prove to be straight, in which case the accurate determination of two points on the line would suffice; and some of the experimental work was adjusted to that theory. The series giving data for but two points on the logarithmic plot of course furnished no evidence as to curvature of the representative line.

For all those cases in which the position of the best representative line could be inferred, with close approximation, from the arrangement of the observational points, a satisfactory adjustment could be made by simply drawing the line and then converting its series of positions into figures; but this procedure would afford no control for the curvature of representative lines in cases where the observational points were few or inharmonious. In order to make the stronger series support the weaker, the plan was adopted of (1) connecting the lines with a formula of interpolation, (2) correlating the constants of the formula with conditions of experimentation, and thus (3) giving deductive control to the lines of the weaker series.

SELECTION OF AN INTERPOLATION FORMULA.

The best interpolation formula is one which embodies the true theory of the relation to which the observations pertain. In the present case the true theory is not known, but there are certain conditions which a theory must satisfy, and these may be used as criteria in the selection of a form for empiric formulas of interpolation. Subject to these criteria, the form selected should serve to minimize the discrepancies between observed and adjusted values.

For the study of the character of the curve to represent best the logarithmic plot of observations, the data for débris of grade (G) were selected. The experiments furnishing those data were all performed by one method, the method using moderate contraction of the trough at outfall; and for that grade the apparent curvature of the logarithmic graph is greater than for most others. The data were first plotted (on logarithmic paper) in groups, each group containing the data for three graphs which pertain to the same width of channel but to different discharges. It was assumed that the three graphs, if correctly drawn, would constitute a system, the one for the medium discharge being intermediate in form and position between the other two; and in drawing them on this assumption the forms were mutually adjusted. Then a rearrangement was made which grouped together data agreeing as to discharge but differing as to width of channel, and further adjustment was made. Selection was finally made of the graph for $w = 0.66$ foot and $Q = 0.734$ ft.^{3}/sec., and this was drawn, through the selected positions, by the aid of a flexible ruler. Thus the curve in figure 19 is a graphic generalization not only from its particular series of observations but from several related series. It was assumed to be a typical or representative curve for the function log $C=f_1(\log S)$; and the corresponding plot on ordinary section paper (the line *BD* in fig. 20) was assumed to represent typically the function $C=f(S)$. The coordinates of the line *BD* are given in Table 5.

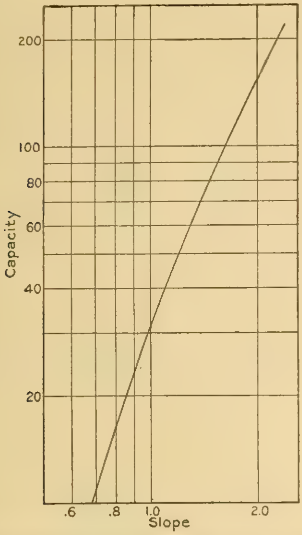

FIGURE 19.—Logarithmic graph of $C=f(S)$, for grade (G), $w=0.66$ foot, $Q=0.734$ ft.^{3}/sec.

TABLE 5.—*Values of capacity for traction, graphically generalized from data of Table 4 (G), for $w=0.66$ foot and $Q=0.734$ ft.^{3}/sec.; corresponding to the curve of log $C=f_1$ (log S) in figure 19, and the curve BD in figure 20.*

Slope.	Capacity.	Slope.	Capacity.
Per cent.	*Gm./sec.*	*Per cent.*	*Gm./sec.*
0.8	16.3	1.8	124
1.0	31.2	2.0	153
1.2	49.9	2.2	185
1.4	72.0	2.4	220
1.6	97.0		

A number of tentative formulas were now compared with this empiric line, their parameters being computed so that they would fit, as nearly as practicable, the values of C in Table 5. Certain functions, including the simpler functions of the circular arc and the exponential function $C=e^{n(S+a)}$, could not be fitted, even approximately, to the data; but the following functions yielded curves closely resembling that of figure 20:

$$C=bS+cS^2+dS^3 \qquad (6)$$
$$C=bS+cS^2 \qquad (7)$$
$$C=a+bS+cS^2 \qquad (8)$$
$$C=-\lambda+bS^n \qquad (9)$$
$$C=b(S-\sigma)^n \qquad (10)$$
$$C=bS^{nS^m} \qquad (11)$$

Functions (6), (7), and (8) are special cases of the general formula of interpolation with integral exponents:

$$x=a+a_1y+a_2y^2 \; . \; . \; . \; +a_ny^n \qquad (12)$$

No. (11) is a somewhat involved power function suggested by results of a preliminary discussion of the laboratory data. Nos. (9) and (10) are special cases of the general parabolic function

$$(x+a)^n=b(y+a_1)^m \qquad (13)$$

and have the virtue of facilitating the graphic treatment of the material. Their logarithmic equivalents are, respectively,

$$\log(C+\lambda)=\log b+n \log S \qquad (14)$$
$$\log C=\log b+n \log(S-\sigma) \qquad (15)$$

and, as each of these is the equation of a straight line, the graphic derivation of the exponent, by means of logarithmic section paper, becomes a simple matter after the value of λ or σ has been determined.

The adjustment of equations (6) to (11) to the specific data in Table 5 gives them the following forms, (6a) being derived from (6), etc.:

$$C=-29.5S+67.59S^2-7.194S^3 \qquad (6a)$$
$$C=-12.86S+44.08S^2 \qquad (7a)$$
$$C=-19.25+16.94S+34.48S^2 \qquad (8a)$$
$$C=-10.0+41.2S^{1.98} \qquad (9a)$$
$$C=70.5(S-0.39)^{1.63} \qquad (10a)$$
$$C=31.2^{\frac{2.68}{S^{0.21}}} \qquad (11a)$$

When the curves corresponding to these equations are plotted for the region covered by the empiric line *BD*, they coincide very closely with that line. The greatest departure is in the curve for (7a), but its divergence is not sufficient to throw it out of apparent harmony with the series of points representing the original observations.

In order to exhibit further the properties of the formulas, their curves were extrapolated in both directions from the locus *BD*. Table 6 contains the numerical data used in plotting the extensions. Figure 20 gives the extensions of the curves for slopes greater than those of the experiments, and figure 21 the extensions for smaller slopes.

TABLE 6.—*Numerical data computed for the construction of curves in figures 20 and 21.*

Equation	(6a)	(7a)	(8a)	(9a)	(10a)	(11a)
Values of *C* corresponding to	*Gm./sec.*	*Gm./sec.*	*Gm./sec.*	*Gm./sec.*	*Gm./sec.*	*Gm./sec.*
S=0	0	0	−19.25	−10.0	Imaginary.	0
S=0.1		−.845		− 9.57	...do	.0014
S=0.2		−.810		− 8.30	...do	.073
S=0.3		.108	−11.07	− 6.20	...do	.490
S=0.4		1.908	− 6.97	− 3.28	.039	1.59
S=0.5		4.59	− 1.96	.45	1.93	3.64
S=0.6		8.15	3.33	4.98	5.54	6.81
S=0.7		12.6	9.50	10.33	10.46	11.14
S=0.8	16.3	17.9	16.36	16.48	16.49	16.67
S=3.0	327	358	332	353	337	323
S=4.0	504	654	589	631	571	616
S=5.0	645	1,039	920	990	849	676
S=6.0	705	1,510	1,315	1,422	1,172	84.
S=7.0	645	2,070	1,741		1,531	998
S=8.0	409	2,718	2,313	2,519	1,923	1,140
S=9.0	−31		2,916		2,355	1,276
S=10.0				3,926	2,818	1,400
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Values of *S* when *C*=0	0 .45 8.94	0 .29	−1.03 .54	−0.49	0.39	0
Values of *S* when *C*=maximum	6.04					
Values of *S* when *C*=minimum	.22					
Values of *S* corresponding to point of inflection	3.33					4.37

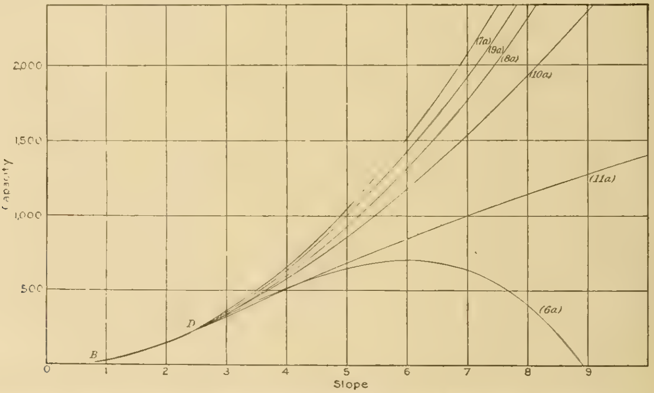

FIGURE 20. Extrapolated curves of $C=f(S)$ for tentative equations of interpolation, and for slopes greater than 2.4 per cent.

The approximate range of this series of experiments is from a slope of 0.8 per cent to one of 2.4 per cent. The extrapolated curves pertain to slopes from 2.4 to 10 per cent and from 0.8 to 0 per cent. The prompt divergence of the lines as they leave the locus to which they were adjusted shows that they have widely different values for purposes of extrapolation, and therefore presumably for purposes of interpolation.

Attention being given first to the curves for higher slopes (fig. 20), it will be observed that four of them ascend with progressively increasing rate. The curve of formula (11a) ascends continuously, but its rate of ascent changes at the slope of 4.37 per cent from an increasing rate to a decreasing rate. The curve of formula (6a) exchanges its increasing rate of ascent for a decreasing rate at the slope of 3.33 per cent, attains a maximum at a slope of about 6 per cent, and crosses the line of zero capacity before reaching the slope of 9 per cent.

The general characteristics of stream traction do not admit of a maximum in the relation of capacity to slope. Capacity for traction is clearly an increasing function of the stream's velocity, and the velocity is clearly an increasing function of the slope. There is reason also to believe that capacity increases at an increasing rate up to the slope corresponding to infinite capacity. There are three forces concerned in traction—first, the force of the current, of which the direction is parallel to the slope; second, a component of gravity, when gravity is resolved in directions parallel and normal to the slope; third, the resistance of the bed, which is a function not only of the others, but inversely of the slope. Within the range of experimental slopes the component of gravity is negligible in comparison with the force of the current, and the influence of slope on the resistance is relatively unimportant; but as the angle of stability for loose material is approached the resistance diminishes rapidly, and at the slope of instability (65 to 70 per cent for river sand) gravity is competent to transport without the aid of current, and the stream's capacity is infinite. All these factors depend on slope, and as the increment to capacity verges on infinity in approaching the slope which limits variation, it is highly probable that capacity grows continuously with slope.

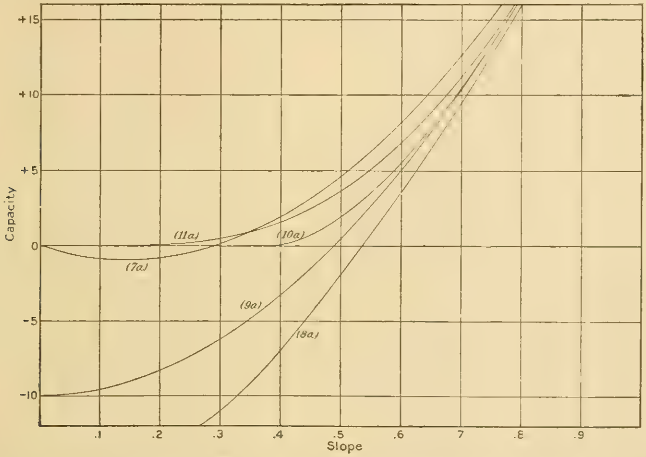

FIGURE 21.—Extrapolated curves of $C=f(S)$ for tentative equations of interpolation and for slopes less than 0.8 per cent.

This criterion suffices for the rejection not only of the specific formulas (6a) and (11a), but also of their types, (6) and (11). In formula (6a) the occurrence of the maximum value of C is determined by the negative coefficient of S^3; and it is true as a general fact that equations of the class indicated by (12) yield maxima whenever the coefficient of the highest power of the independent variable is negative. It is possible, or perhaps probable, that if each series of laboratory values were to be formulated under (7) or (8) the conditions for maxima would be found to occur. On the whole, the extrapolations for higher slopes tend to restrict choice to forms (9) and (10), with some reservation as to forms (7) and (8).

Figure 21 gives extrapolated curves for slopes less than 0.8 per cent and represents the same equations as figure 20, except that the curve for (6a) is omitted. It will be observed that it magnifies greatly the space between 0 and B in figure 20, the scale of slopes being 10 times and the scale of capacities 100 times as large. The implications of the functions for low slopes are specially important because extrapolation from laboratory conditions to those of natural streams will nearly always involve the passage from higher to lower slopes.

Curves (7a) and (11a) reach the origin of coordinates—that is, their equations indicate that at the zero of slope there is no capacity for traction. Formula (11a) gives small but finite capacities for very low slopes; but under formula (7a) finite capacities cease when the slope falls to 0.29 per cent, and for lower slopes there is indication of negative capacities. If the conditions of traction permitted, negative capacity might be interpreted as capacity for traction upstream; but as this is inadmissible, the negative values may be classed as surd results arising from the imperfection of the correlation between an abstract formula and a concrete problem. The curves of (8a) and (9a) also intersect the axis of slope at some distance from the origin, and their extensions indicate negative capacity. The curve of (10a) becomes tangent to the axis of slope at the point corresponding to a slope of 0.39 per cent and there ends, having no continuation below the axis. It is the real limb of a parabola of which all other parts are imaginary. It expresses to the eye the implication of formula (10a) that traction ceases when the slope is reduced to 0.39 per cent, and that its cessation is not abrupt but gradual; and also the implication of the general formula (10) that traction ceases when the slope is reduced to the value σ.

It is a matter of observation that when slope is gradually reduced, the current becoming feebler and the capacity gradually less, the zero of capacity is reached before the zero of slope. For each group of conditions (fineness, width, discharge) there is a particular slope corresponding to the zero of capacity. It is also a matter of observation that the change in capacity near the zero is gradual. Formulas (7a), (8a), (9a), and (10a) therefore accord with the data of observation in the fact that they connect the zero of capacity with a finite slope; formula (11a), which connects zero capacity with zero slope, is discordant. Also, formulas (10a) and (11a) accord with the data of observation in that they make the approach of capacity to its zero gradual; while formulas (7a), (8a), and (9a), which make the arrival of capacity at its zero abrupt, are in that respect discordant.

But one of the formulas (10a), shows qualitative agreement with both of the criteria applied through extrapolation to low slopes; and that formula is one of the two which respond best to the criterion applied through extrapolation to high slopes. That type of formula, or

$$C=b_1\,(S-\sigma)^n \text{ . . . . } (10)$$

was therefore selected for the reduction of the more or less irregular series of observational values of capacity to orderly series better suited for comparative study.

In rewriting the formula the coefficient is changed from b to b_1, because corresponding coefficients b_2, b_3, etc., are to be used in a series of formulas expressing the relations of capacity to various conditions. As slope is a ratio between lengths, $(S-\sigma)^n$ is of zero dimensions and b_1 is of the unit C; it is the value of capacity when $S-\sigma=1$.

The slope which is barely sufficient to initiate traction has been defined (p. 35) as the *competent slope.* To whatever extent σ represents the competent slope the formula has a rational basis. The local potential energy of a stream, or the energy available at any cross section in a unit of time, is simply proportional to the product of discharge by slope or, if the discharge be constant, is proportional to the slope. So long as the slope is less than that of competence the energy is expended on resistances at contact with wetted perimeter and air and on internal work occasioned by those resistances. When the slope exceeds the competent slope, part of the energy is used as before and part is used in traction. The change from competent slope to a steeper slope increases the available energy by an amount proportional to the increase of slope, and the increase of energy is associated with the added work of traction. Capacity for traction, beginning at competent slope, increases pari passu with the increase of the excess of slope above the competent slope, and there is manifest propriety in treating it as a function of the excess of slope rather than of the total slope. It is of course also a function of the total slope; but an adequate formula for its relation to the excess of slope may reasonably be supposed to be simpler than a formula for its relation to total slope. If σ represents competent slope, then the relation of capacity to $S-\sigma$ should be simpler than its relation to S.

Instructive information as to the relative simplicity of the two functions is obtained by comparing their logarithmic graphs. In figure 22 the curved line AB has been copied from the curve in figure 19. It is the graph of $\log C = f(\log S)$ for grade (G), width 0.66 foot, and discharge 0.734 ft.^{3}/sec. If for S we substitute $S-0.3$, we modify the graph by moving each point of it to the left by an amount equal to $\log S - \log (S-0.3)$; and we produce the line CD, which is the graph of $\log C = f_{\text{II}}(\log (S-0.3))$. If in similar manner we derive the graph of $\log C = f_{\text{III}}(\log (S-0.6))$, the result is the line EF. CD curves in the same direction as AB but less strongly; EF curves in the opposite direction. It is evident that the three curves belong to a continuous series, and that somewhere between CD and EF a member of the series is straight or approximately straight. That straight line, GH, is the graph of $\log C = f_{\text{IV}}(\log (S-0.39))$; but as it is straight, its equation may be written

$$\log C = \log b_1 + n \log (S-0.39),$$

in which $\log b_1$ is the ordinate of the intersection of the line with the axis of $\log C$, and n is the trigonometric tangent measuring the inclination of the line to the axis of $\log S$. This is identical with equation (15) except that 0.39 appears in place of σ; and in fact the value of σ in equation (10a) was computed graphically by means of the logarithmic plot.

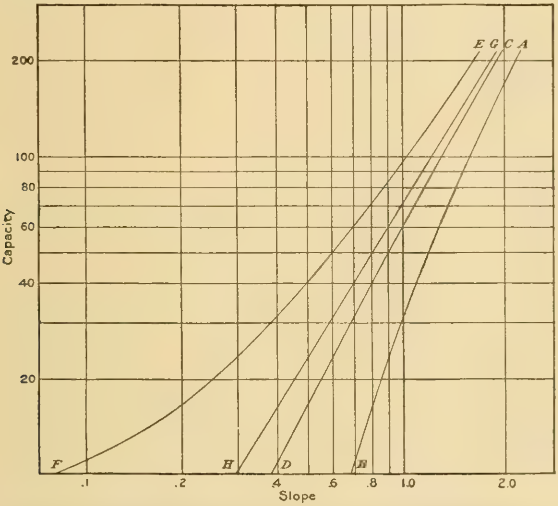

FIGURE 22.—The relation of σ in $C = f(S-\sigma)$ to the curvature of the logarithmic graph.

The line AB, being the graph of $\log C = f_{\text{I}}(\log S)$, is also the logarithmic graph of $C = f(S)$. The line GH, being the graph of $\log C = f_{\text{IV}}(\log (S-\sigma))$ is also the logarithmic graph of $C = f_{\text{V}}(S-\sigma)$. Their relation in respect to simplicity is that of the curve to the straight line.

In view of these suggestions of harmony it is peculiarly pertinent to inquire whether σ is actually representative of competent slope; and it will be convenient to make that inquiry in connection with the determination of values of σ for the several series of observations on capacity and slope.

THE CONSTANT σ AND COMPETENT SLOPE.

In the experimental data for graded débris—Table 4, (A) to (H)— are 117 series of values of capacity and slope. After these had been plotted and inspected in a comparative way, it was decided to restrict the main discussions to 92 series only, the discarded series being all short as well as somewhat discrepant among themselves. Of the 92 series retained, only 30 afford information as to the corresponding values of σ; that is, only 30 of the logarithmic plots exhibit curvature so definitely that the approximate magnitudes of the constants necessary to eliminate it can be inferred. In some of the remaining series the observations are not so distributed as to bring out the curvature. For others the observational positions on the plots are too widely dispersed to give good indication of the character of the best representative line.

On the 30 logarithmic plots the curves approximately representing the observations were drawn, and the values of σ necessary to replace the curves by straight lines were computed graphically in the manner just indicated. These values are given, to the nearest tenth of 1 per cent of slope, in Table 7, where they are arranged with reference to the conditions of the experiments.

TABLE 7.—*Values of σ in $C=b_1(S-\sigma)^n$, estimated from logarithmic plots of observations.*

Grade	F	Range of F	w (feet).	Values of σ for discharge (ft.³/sec.) of—							
				0.093	0.182	0.363	0.545	0.734	0.923	1.021	1.119
(A)	25,200	1.77	0.66	—	—	....	—	....	....	....	....
			1.00	....	—	—	....	—	....	....	....
			1.32	....	0.2	0.1	....	—	....	....	....
			1.96	....	....	—	....	—	....	....	....
(B)	13,400	2.35	.23	0.7	.4	....	....	....	....	....	....
			.44	.5	.0	....	....	....	....	....	....
			.66	—	—	—	—	....	....	....	....
			1.00	....	—	.1	—	0.1	....	....	....
			1.32	....	—	—	—	—	....	....	....
			1.96	....	....	—	—	—	....	....	....
(C)	5,460	2.85	.44	.4	—	....	....	....	....	....	....
			.66	.2	.1	—	0.1	—	....	....	....
			1.00	....	.3	.1	—	.1	....	....	—
			1.32	....	—	.1	—	.1	....	....	....
			1.96	....	....	.3	—	—	....	....	—
(D)	1,460	3.58	.66	—	—	....	—	....	....	....	....
			1.00	....	—	—	—	—	....	....	....
			1.32	....	....	—	....	—	....	....	....
(E)	142	12.65	.66	....	—	—	....	—	....	....	—
			1.00	....	.0	.0	....	.0	....	....	—
			1.32	....	....	—	....	—	....	....	—
(F)	22.1	2.15	.66	....	—	—	....	—	....	....	....
			1.00	....	—	—	....	—	....	....	—
			1.32	....	....	—	....	—	....	....	—
(G)	5.9	2.92	.66	....	....	.6	....	.4	....	....	0.3
			1.00	....	....	.6	....	.3	....	....	.3
			1.32	....	....	—	....	.4	....	....	—
(H)	2.0	2.51	.66	....	....	—	....	.6	....	....	.4

NOTE.—The horizontal dashes indicate series of observations to which values of σ are to be assigned.

The same table shows the distribution of the experimental series which fail to give values of σ but to which it is proposed to assign values. In order to assign these values properly it is necessary to know the laws of variation of σ with reference to the conditions of experimentation. These are suggested in part by the roughly determined values of the table and are otherwise indicated by general considerations. The variations are connected with at least three conditions—discharge, width, and fineness—and are less surely connected with range of fineness.

Considering first the variation of σ with discharge and giving attention in the table to values of σ falling in the same horizontal line, we find by inspection that invariably the value for a larger discharge is either less than or equal to the value for the corresponding smaller discharge. The indication is that σ is a decreasing function of discharge. This relation might have been inferred from general considerations, on the theory that σ represents competent slope. Competent slope is the slope giving competent velocity along the bed, but bed velocity also varies directly with discharge. With large discharge less slope is necessary to induce competent velocity; with small discharge more slope. In other words, competent slope varies inversely with discharge. In a preliminary discussion of the traction data for débris of grades (B) and (C) it was found that capacity is more sensitive to changes in slope than to changes in discharge. The relation of capacity to slope and discharge jointly being tentatively represented by

$$C \propto S^n \, Q^m \text{ - - - - - - - - - (16)}$$

the values of n and m were computed for many different conditions, and it was found that on the average $\frac{m}{n}=0.34$. There is, however, considerable variation in the ratio, and it is relatively large when C is small. On plotting the values of the ratio in relation to C and graphically extrapolating, it was found that when $C=0$ the ratio is about 0.5. The condition of zero capacity is that of competent bed velocity and competent slope.

For any particular value of C in (16) the product of S^n by Q^m is constant, or

$$S^n \propto \frac{1}{Q^m}$$

whence

$$S \propto \frac{1}{Q^{\frac{m}{n}}}$$

But, as we have just seen, when C has the particular value $C=0$, $\frac{m}{n}=0.5$. Therefore competent slope varies inversely as $Q^{0.5}$. Its assumed representative, σ, is assumed to vary inversely with the square root of discharge.[1]

Turning now to the relation of σ to width, w, and examining Table 7, we see that σ is not exclusively either an increasing or a decreasing function of w. Where the smallest widths are concerned, as with $Q=0.093$ ft.^{3}/sec. and $Q=0.182$ ft.^{3}/sec., for grades (B) and (C), the function is decreasing. Where the greater widths are concerned it is for the most part increasing. There is a rational explanation for such double relationship in the case of competent slope.

Figure 23 represents two troughs in cross section. Each has a bed of débris, and they are assumed to be carrying the same total discharge. In the wider there is less discharge for each unit of width, and the tendency of the smaller discharge is to reduce velocity. Therefore to maintain a particular velocity—namely, the competent velocity—the tendency is to produce a relatively steep slope. So far as this factor is concerned, competent slope is relatively steep for a wider trough. But there is another factor; the velocity is influenced by the resistance of the sides of the trough. This resistance is greater where the water is deeper, because the surface of contact is broader; and the water is deeper in the narrower trough. The tendency of the resistance is to reduce velocities and therefore to make the slope for competent velocity steeper in the narrower trough.

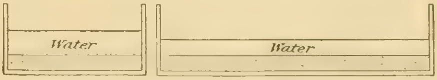

FIGURE 23.—Diagrammatic sections of laboratory troughs, illustrating relation of current depth to trough width.

In very wide troughs the influence of the sides is of minor importance, the influence of discharge per unit width dominates, and the competent slope varies directly with the width. In very narrow troughs the influence of the sides dominates, and the competent slope varies inversely with the width. For some intermediate width the two tendencies are balanced, and the competent slope has its minimum value. In figure 24 abscissas measured from O represent width of trough, and ordinates represent competent slope. The curve sketched, while not quantitative, has adequate basis for its broader features and shows the general character of the relation of competent slope to width. From its minimum it ascends gradually on the side of greater width, and on the side of lesser width rises with relative rapidity toward a vertical asymptote near the axis of competent slope. These various characters are approximately paralleled by the variations of σ as shown in the table.

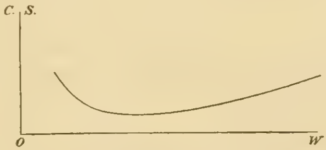

FIGURE 24.—Ideal curve of competent slope ($C. S.$) in relation to width of trough (W).

The relation of σ to fineness does not come out very clearly in Table 7, and a different arrangement is therefore given in Table 8, which omits the values of σ not affording comparison and adds three interpolated values. The general fact thus shown is that σ increases as fineness diminishes, but to this there are two exceptions. The more important exception is in grade (E), of which all values of σ are less than the corresponding values for either grade (C) or grade (G). The values for grades (B) and (C) appear to be about the same, although the two grades differ notably in fineness. The exceptions are associated with peculiarities of the grades with respect to range of fineness. In grade (E) the range for bulk fineness is about twice as great as in any of the other grades; and if this character indicates the cause of its abnormally small values of σ, then the abnormally high values in grade (B) are explained by its small range of fineness as compared to the range of grade (C).

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[1] The preliminary discussion on which is based $\sigma \propto \frac{1}{Q^{0.5}}$ did not have the advantage of the formula using σ. A rediscussion, to be found in Chapter V, yields $\sigma \propto \frac{1}{Q^{0.77}}$: but it was not practicable to give the adjustment the benefit of this later work without repeating the greater part of the computations of the paper. It is not believed that the advantage to the results would be commensurate with the labor involved.

TABLE 8.—*Values of σ, from Table 7, arranged to show variation in relation to fineness of débris.*

Grade		(B).	(C).	(E).	(G).	(H).
Fineness (F_2)		13,400	5,460	142	5.9	2.0
Range of fineness		2.35	2.85	12.65	2.92	2.51
Width.	Discharge.	Values of σ				
0.44	0.093	0.5	0.4	......	......	......
.44	.182	.0	[.2]	......	......	......
.66	.363	......	[.1]	......	0.6	......
.66	.734	......	[.1]	......	.4	0.6
1.00	.182	......	.3	0.0	......	......
1.00	.363	.1	.1	.0	.6	......
1.00	.734	.1	.1	.0	.3	......
1.32	.734	......	.1	......	.4	......

The values of σ inferred from the logarithmic plots are not sufficiently precise to yield quantitative laws of the relations of σ to fineness and the range of fineness, and it is again necessary to seek instead the laws governing competent slope. Does competent slope vary inversely with fineness, and what is its law? Does competent slope vary inversely with range of fineness, and what is its law?

Inasmuch as fine débris is moved by a relatively slow current and as the force of the current is a direct function of slope, the competent slope for fine débris is less than for coarse. If we accept the thesis of Leslie and Hopkins (see p. 16) that competent bed velocity (V_{cb}) varies with the sixth root of the volume or mass of the débris particle, then, since bulk fineness is the reciprocal of volume,

$$V_{cb} \propto \frac{1}{F_2^{1/6}}$$

If we assume, from the Chezy formula, that mean velocity of current is proportional to the square root of slope and apply it to component mean velocity (V_{cm}) and competent slope (S_c), we have

$$V_{cm} \propto S_c^{0.5}$$

If we further assume that bed velocity is proportional to mean velocity, then, by combining the three proportions and reducing, we obtain

$$S_c \propto \frac{1}{F_2^{0.33}} \qquad (17)$$

As each of the three assumed laws is subject to important qualifications, the product of their combination must be regarded as but a rough approximation to the law connecting competent slope with fineness.

Further light on the law is afforded by some experiments made for the specific purpose of determining competent slope. In these experiments the discharge remained constant while the velocity was modified by changing the width of the outfall. The slope of the bed had been prepared in advance, and the slope of the water surface was measured for each width of outfall. At each stage of the experiment the movement of grains of débris along the bottom was noted by such phrases as "many," "several," "few," "very few," "none," the words being used in that order as a sort of scale. Competent slope was inferred from a comparison of these notes with the recorded slopes of the water surface. The results are given in Table 9.

In a closely related series of experiments, Table 10, a slope of débris was prepared in advance, a small discharge was passed over it, and the discharge was progressively increased, with notes on the movement of débris grains. These experiments gave competent discharge.

In each series the depths were measured, and from these the mean velocities (V_m) were computed.

The experimental determinations were indefinite for several reasons. In the first place, a stream with the critical bottom velocity does not transport débris and therefore does not establish its own slope of bed. The slopes artificially prepared were of necessity imperfectly adjusted. In the next place, the prepared slopes did not imitate the natural diversity of detail but were plane. When a current of competent velocity passed over one of them it immediately began to shape the bed into dunes, and as the modeling proceeded the activity of transportation increased. After the dunes were formed, a smaller general velocity, or a less discharge, or a lower general slope was competent. The experiments being made in sets, the first of a set gave a result from the plane bed and the others from a more or less diversified bed.

In the third place, the particles composing one of the experimental grades of débris were not of uniform mobility. Not only were they of diverse size, as indicated by the "range of fineness," but they were different in shape and in specific gravity, so that some were able to resist a considerably stronger current than others. The competent slope for the least mobile particles was materially steeper than that for the most mobile, and no mode of gaging average mobility was discovered.

TABLE 9.—*Experimental data on competent slope.*

Grade of débris.	Width of trough.	Width of contractor.	Discharge.	Slope of débris.	Slope of water.	Depth.	Mean velocity.	Notes on movement of débris.
	Feet.	*Feet.*	*Ft.³/sec.*	*Per ct.*	*Per ct.*	*Feet.*	*Ft./sec.*	
(B).....	1.00	0.30	0.363	0.048	0.01	0.490	0.74	A very few grains moving. Small dunes forming.
		.40	.363	.03	.06	.425	.85	Many grains moving. Dunes forming.
		.30	.363	.028	.03	.475	.76	A very few grains moving. Some dunes forming.
C).....	1.00	.30	.363	.10	.01	.451	.80	A very few grains moving in a few places.
		.40	.363	.10	.042	.391	.93	Many grains moving. Dunes forming.
		.30	.734	.10	.045	....	....	Dunes forming rapidly.
(D).....	1.00	.30	.363	.02	.21	.465	.78	No grains moving.
		.40	.363	.02	.34	.418	.87	An occasional grain moving.
		.30	.734	.02	.33	.743	.99	Very few, if any, grains moving.
		.40	.734	.02	.57	.658	1.12	Many grains moving. Dunes forming.
		.40	.363	.06	.03	.392	.93	A very few grains moving. No dunes forming.
		.40	.363	.10	.055	....	....	Very few grains moving.
		.45	.363	.10	.054	.373	.97	Some small grains moving.
		.50	.363	.10	.056	.357	1.02	Several small grains moving. No dunes forming.
		.55	.363	.10	....	....	....	Many grains moving.
(E).....	1.00	.40	.363	.05	.043	.387	.94	No transportation.
		.40	.734	.035	.025	.618	1.19	Do.
		.50	.363	.035	.057	.357	1.02	Do.
		.50	.734	.035	.069	.562	1.31	Some transportation in lower half of slope.
		.60	.363	.05	.086	.330	1.10	Very few grains moving in lower half of slope.
		.60	.363	.10	.096	.314	1.16	A few grains moving.
(G).....	1.00	.70	.363	.40	.22	.256	1.42	No grains moving.
		.87	.363	.40	.29	.238	1.52	Do.
		.87	.363	.50	.46	.225	1.61	A few grains moving at one place.
		.87	.734	.50	.46	.360	1.01	A few grains moving in places.
		.87	.363	.65	.70	.201	1.80	Very few, if any, grains moving.
		.87	.363	.80	.80	.184	1.98	An occasional grain moving.
		.87	.363	1.00	.93	.173	2.10	Several grains moving in center half of slope.

When an experiment was begun with a velocity well below competence, and the velocity was gradually increased, the first movement detected would be the saltation of some small or light particle, and then the number of particles moving would gradually grow with the quickening of current.

An attempt to correlate the "notes on movement of débris" in Table 10 for a discharge of 0.363 ft.³/sec. gave the following values of water slope for equivalent phases of movement:

Grade..............	(B)	(C)	(D)	(E)	(G)
Slope of water (per cent)............	0.03	0.03	0.06	0.10	0.93

By assuming the power function $S_c = a\,F_2^n$, or $\log S_c = \log a + n \log F_2$, and plotting $\log S_c$ in relation to $\log F_2$, the value found for n is about -0.5, but it has a large uncertainty. The plot, figure 25, shows the competent slope for grade (E) smaller than would be indicated by

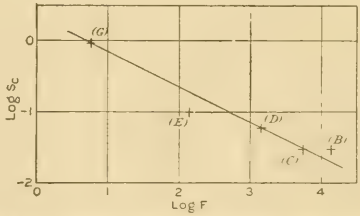

FIGURE 25.—Logarithmic plot of competent slope in relation to fineness of débris.

its neighbors, but not so much smaller as is the value of σ for grade (E) in Table 7. It also makes the competent slope for grade (B) aberrant in the same sense as the corresponding value of σ. The data are too vague to give much value to such correspondences; but the broader resemblances aid in connecting σ with competent slope.

TABLE 10.—*Experimental data on competent discharge.*

Grade of débris.	Width of trough.	Width of contractor.	Discharge.	Slope of débris.	Depth.	Mean velocity.	Notes on movement of débris.
	Feet.	*Feet.*	*Ft.³/sec.*	*Per ct.*	*Feet.*	*Ft./sec.*	
(E)....	1.32	0.90	0.039	2.00	......	......	Many grains moving. Dunes quickly formed.
			.019	1.95	0.015	0.96	Some grains moving; many moving as small channels are formed or surface becomes rough.
			.019	1.00	.014	1.03	No grains moving.
			.039	1.00	.026	1.14	Many grains moving.
			.039	1.00	.024	1.23	Several grains moving. Dunes forming.
			.019	1.00	.018	.80	No grains moving.
	1.00	.72	.010	2.00	.015	.67	A few grains moving in a few places. Dunes forming.
			.019	1.94	.025	.76	Many grains moving. Dunes forming.
		.92	.019	1.00	....	....	A few grains moving in a few places.
			.029	1.00	....	....	Several grains moving in several places.
			.039	.50	.053	.74	No grains moving.
			.058	.50	.060	.96	A few grains moving in a few places.
			.075	.50	.065	1.15	Several grains moving in several places.
			.093	.50	.070	1.33	Transportation.
	.66	.46	.010	2.00	.022	.69	A few grains moving in a few places.
			.019	2.00	.028	1.03	Several grains moving in nearly all parts of trough.
			.010	1.13	....	....	No motion.
			.019	1.13	.042	.69	A few grains moving in a few places.
			.039	1.13	.050	1.19	Many grains moving. Surface becoming rough.
(F)....	.66	.46	.039	2.51	.043	1.36	An occasional grain moving. Several grains moving after a time.
			.058	1.05	....	....	No grains moving.
			.075	1.05	.071	1.59	A few grains moving in a few places.
			.093	1.05	.092	1.52	Several grains moving in some places.
			.111	1.05	....	....	Many grains moving.
	1.00	(?)	.146	1.00	.086	1.70	Few grains moving in some places.
			.164	1.00	.093	1.77	Several grains moving.
(G)....	.66	.45	.146	1.10	.119	1.84	No grains moving.
			.164	1.10	.126	1.95	Very few grains moving.
			.182	1.10	.139	1.96	A few grains moving near middle of trough.
			.200	1.10	.143	2.10	A few grains moving.
			.218	1.10	.153	2.13	Several grains moving in lower half of trough.
			.164	1.58	.112	2.20	Some grains moving in lower half of trough.
			.182	1.58	.104	2.63	Several grains moving in lower half of trough, but very few in upper half.
			.200	1.58	.104	2.88	Many grains moving in lower half, but few in upper half.
			.146	2.05	.106	2.07	Several grains moving in middle of trough; many in lower part. Cutting of grade.
			.111	2.05	.088	1.89	A few grains moving.
			.093	2.05	.088	1.58	Very few grains moving.
			.075	2.05	.070	1.61	No grains moving.
			.058	2.50	.052	1.61	Do.
			.075	2.50	.054	2.08	A few grains moving.
			.093	2.50	.072	1.95	Many grains moving.
	1.00	.70	.182	1.00	.124	1.47	No grains moving.
			.218	1.00	.141	1.55	No (or very few) grains moving.
			.255	1.00	.153	1.67	Very few moving.
			.290	1.00	.159	1.84	Many grains moving.
			.182	1.45	.089	2.04	Very few small grains moving.
			.218	1.45	.098	2.23	Several grains moving.
			.255	1.45	.105	2.43	Many grains moving.
			.182	1.90	.090	2.02	Several grains moving.
			.146	1.90	.080	1.83	Very few grains moving.
			.111	1.90	.059	1.88	No grains moving.
			.093	2.52	.061	1.52	Do.
			.111	2.52	.067	1.66	A very few grains moving in part of trough.
			.128	2.52	.074	1.73	A few grains moving, except near head of trough.
			.146	2.52	....	....	Many grains moving. Grade cutting in places.
	1.32	.92	.272	1.05	.115	1.79	No grains moving.
			.327	1.05	.125	1.99	Very few grains moving.
			.345	1.05	.128	2.04	A few grains moving.
			.363	1.05	.130	2.11	Several grains moving.
			.218	1.40	.075	2.21	Very few grains moving near center of trough.
			.237	1.40	.079	2.27	None moving except at middle of trough.
			.255	1.40	.084	2.27	Very few moving except at middle of trough.
			.272	1.40	.090	2.28	A few grains moving.
			.290	1.40	.099	2.22	Several moving in middle and lower parts; very few in upper.
			.218	2.00	.079	2.09	A few grains moving.
			.237	2.00	.090	1.99	Several grains moving in middle part of trough.
			.255	2.00	.097	1.98	Several grains moving.
			.146	2.50	.055	2.01	Very few grains moving.
			.164	2.50	.061	2.04	Several grains moving.
			.182	2.50	.069	1.99	Do.
(H)...	.66	.46	.363	1.10	.212	2.57	Occasionally a grain moving.
			.454	1.10	.260	2.62	A few grains moving in lower half of trough.
			.545	1.10	.399	2.74	Several grains moving in lower two-thirds of trough, and occasionally a grain in upper third.
			.639	1.10	.329	2.91	Several grains moving in middle third of trough; a few in upper and lower parts.
		.45	.272	1.30	.163	2.49	Occasionally one grain moving.
			.308	1.30	.171	2.70	Some grains moving below middle; 1 to 3 grains in a cross section.
			.345	1.30	.184	2.82	2 to 5 grains moving in a cross section.
			.182	2.05	.132	2.05	No grains moving.
			.218	2.05	.137	2.39	A few grains moving in lower three-fourths of trough.
			.255	2.05	.141	2.72	Many grains moving in lower three-fourths of trough.

In treating the data of Table 9, the assumption was made that the note "several grains moving" corresponds to competent slope; and averages were found of the values of mean velocity and depth.[1] These are:

Grade	(E)	(F)	(G)	(H)
Mean velocity (ft./sec.)	1.10	1.52	2.14	2.83
Depth (foot)	0.020	0.092	0.108	0.218

When the logarithms of these numbers are plotted the positions fall well in line, and the representative line gives (V_{cm} indicating the mean velocity corresponding to competent bed velocity)

$$V_{cm}=\frac{3.2}{F_2^{0.22}} \text{ - - - - - - - - - - - - } (18)$$

Assuming again that bed velocity is proportional to mean velocity, and again assuming the validity of the Chezy formula, we obtain from (18)

$$S_c \propto \frac{1}{F_2^{0.44}} \text{ - - - - - - - - - - - - } (19)$$

The two values of the exponent of F_2 derived from the experiments, namely, -0.44 and -0.50, are both larger than the deductive value, -0.33, of equation (17), but the disparity is quite natural in view of the indefiniteness of the data and the uncertainties of the assumptions. Collectively the values indicate an order of magnitude.

The influence of range of fineness on competent slope appears to be of the same nature as its influence on σ, though much less pronounced, but the determinations of competent slope are too indefinite to give the greatest value to the comparison. It is significant, however, that while the logarithmic plots for grade (E) and width 1.00 and for three different discharges (Table 7) all yield values of σ less than 0.05 per cent, the experiments on competent slope (Table 9) record for one of the discharges "no grains moving" with a slope of 0.21 per cent, and for another "very few, if any, grains moving" with a slope of 0.33 per cent. The values of σ in this case fall far below those for the most mobile components of the débris grade which has the largest range of fineness. The general facts appear to be that σ varies decreasingly with range of fineness, and that competent slope is subject to a variation of the same kind, which may or may not be of the same magnitude.

The cause of this variation is not surely known, but a plausible suggestion in regard to it may be made. In the experiments with mixtures of two or more grades it was found that before the slope had been established, especially when low velocities were used, the current tended to sort the débris, building deposits with the coarser part and delivering the finer material at the end of the trough. In experiments with a single grade the same tendency doubtless existed. It was in fact observed in connection with dunes and antidunes, which sometimes showed a shading in color due to partial sorting with respect to density, the heavier particles being dark, the lighter pale. As the differences of size within a grade were not such as to appeal strongly to the eye, considerable sorting with respect to size might take place without attracting attention. With the ordinary routine of the experiments, which began in each series with low slopes and velocities and gradually increased them, the influences of such sorting may have been systematic, and thus may have modified that relation of values which finds expression in the constant σ. The result of such influence would be more pronounced for grade (E) than for grades with smaller range of fineness. It is easy to see also that an allied influence may have affected to some extent the interpretation of the experiments on competent slope.

The variations of σ are paralleled in so many ways by the variations of competent slope as to leave little doubt that the one is in some way representative of the other. It can not be said that the constant σ, arbitrarily introduced to rectify curves and thereby facilitate interpolation, is the equivalent of the slope of competence—if for no other reason than that the competent slope for a grade of débris made of unequal grains eludes precise definition—but it may well be a complex function of the competent slopes of all the different sorts of grains contained in one of the laboratory grades.

For the practical purpose of obtaining values of σ for use in formulas of interpolation, the preceding discussion yields a large body of pertinent information. Sigma varies inversely with a power of discharge, approximately the 0.5 power. It varies inversely with a somewhat smaller power of the bulk fineness of débris. It varies inversely with the range of fineness of the grades of débris, this variation serving to qualify the preceding. It varies with width of channel, the variation including a minimum. Without attempting to give definite symbolic expression to these laws of variation, they were applied to the practical problem, and by a series of adjustments the skeleton of values of σ in Table 8 was developed into a system covering the whole range of experimental conditions. That system is presented in Table 11.

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[1] A few series of observations on competent velocity have been made by others. They pertain chiefly to flume traction and are cited in Chapter XII. Login, whose results are given in Chapter VII, used the methods of stream traction but omitted to measure the sizes of materials transported.

TABLE 11.—*Values of σ, in per cent of slope, as adjusted for use in interpolation equations of the form $C=b_1\,(S-\sigma)^n$.*

Grade.	Width (feet).	Values of σ for discharge ($ft.^3$ *sec.*) of—							
		0.093	0.182	0.363	0.545	0.734	0.923	1.021	1.119
(A).....	0.66	0.40	0.20	......	0.04	......	......	......	......
	1.00	......	.12	0.07	......	0.05	......	......	......
	1.32	......	.17	.10	......	.07	......	......	......
	1.96	......	......	.17	......	.10	......	......	......
(B).....	.23	.70	.60	......	......	......	......	......	......
	.44	.50	.10	......	......	......	......	......	......
	.66	.30	.10	.08	.07	......	......	......	......
	1.00	......	.12	.08	.06	.06	......	......	......
	1.32	......	.17	.12	.10	.08	......	......	......
	1.96	......	......	.18	.14	.12	......	......	0.10
(C).....	.44	.40	.20	......	......	......	......	......	......
	.66	.16	.11	.08	.06	.04	......	......	......
	1.00	......	.15	.11	.09	.07	......	......	.06
	1.32	......	.22	.16	.13	.11	......	......	......
	1.96	......	......	.24	.20	.17	......	......	.14
(D).....	.66	.19	.14	......	.08	......	......	......	......
	1.00	......	.17	.12	.12	10	0.08	......	......
	1.32	......	......	.16	......	.11	......	......	......
(E).....	.66	......	......	.09	......	.06	......	......	......
	1.00	......	.08	.06	......	.04	......	......	.03
	1.32	......	......	.04	......	.03	......	......	.02
(F).....	.66	......	.33	.21	......	.17	......	......	......
	1.00	......	.44	.31	......	.22	......	......	.17
	1.32	......	......	.39	......	.28	......	......	.23
(G).....	.66	......	......	.50	......	.36	......	......	.27
	1.00	......	......	.58	......	.41	......	......	.33
	1.32	......	......	.71	......	.50	......	......	.40
(H).....	.66	......	......	.80	......	.56	......	......	.48

INTERPOLATION.

The values of σ having been assigned, the data of Table 4 were once more plotted on logarithmic paper, the ordinates again representing load or capacity, and the abscissas representing $S-\sigma$, or observed slope less the constant slope σ. As in the preliminary plotting for inspection, the primary data were (1) the estimates of load from the quantity of débris delivered at the end of the trough and (2) the associated slopes of the bed of débris, and accessory data were added with distinctive notation. The secondary data were used chiefly to indicate the relative precision of the primary data, the primary having greater weight when agreeing more closely with the secondary. The illustrative plot, figure 26, shows only the primary data.

The next step was to draw through and among the observational points the best representative straight line. It is a property of the logarithmic plot that its distances represent ratios, and the scale of ratios is everywhere the same. Similar errors of observational positions are shown by similar distances in all parts of the plot, provided the errors are considered as fractional parts of the plotted quantities. Each observational point should be given the same influence in determining the representative line, provided the (fractional) probable errors of the observations are the same. In this case, however, the fractional probable errors for low capacities and slopes are much greater than for high capacities, and the best representative lines can not be drawn without consideration of weights. Adjustment by the least-squares method was considered and experiments were tried, but the labor entailed by the necessity of using weights was not thought to be warranted by the quality of the data. The following simpler and less rigorous method was employed:

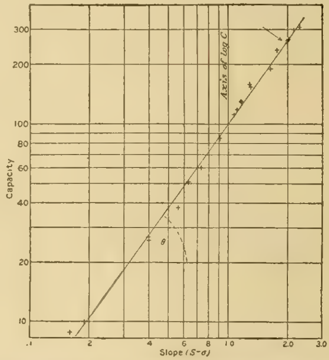

FIGURE 26.—Illustration of the method used to adjust values of capacity, in relation to slope, by means of a logarithmic plot of observed values of capacity in relation to slope minus σ.

A group of observational points corresponding to the highest slopes was selected by inspection of the plot, and its center of gravity was computed by a graphic method. In the case shown by figure 26, the group includes six points and the center of gravity is the point indicated by an arrow. The representative line was made to pass through this point and was otherwise adjusted to position by eye estimate, with consideration of all the observational points and their supposed weights. By this method the observations of greatest weight were enabled to fix one point on the line and were also consulted, along with observations of less weight, as to its direction or attitude. The method obviously left much to personal judgment, but had a rigorous method been attempted it would have been difficult or impossible to avoid the use of nonrigorous judgment in the assignment of weights.

The line when drawn is a generalized expression, for a single series of observations, of the relation of capacity to slope less σ. It is the graphic equivalent, or graph, of a specific equation of the form

$$\log C = \log b_1 + n \log (S - \sigma) \quad \text{. . . . . . (20)}$$

which is the logarithmic equivalent of

$$C = b_1 (S - \sigma)^n \quad \text{. . . . . (10)}$$

The inclination of the line ($\tan \theta$) was next measured, or computed, giving the numerical value of n; and its point of intersection with the axis of $\log C$ was determined, giving the value of b_1. The values of n, b_1, and σ for the 92 series are shown in Table 15.

The graph was used, instead of the equivalent equation, in computing values of C corresponding to systems of values of S. The results are given in Table 12 and constitute the data for further generalizations. To compute values of C for a particular observational series, the value of σ for the series was first subtracted from each value of S in the adopted system, then each remainder $(S - \sigma)$ was applied as an argument to the graph and the corresponding value of C read off. The range of values thus computed and tabulated was either limited by the range of observational values, or else included a moderate extrapolation, which never exceeded 10 per cent of the observational range.

PRECISION.

If the position of the straight line in each of the logarithmic plots (fig. 26) had been determined by rigorous methods, it would be possible to compute by rigorous methods the probable errors of the quantities implied by its position. As only approximate methods were employed in placing them, only approximate measures of precision are attainable, and an elaborate treatment would be unprofitable. The precision of the attitude of the line, corresponding to the quantity n, has not been estimated; but computation has been made of the precision of its position in the direction of the axis of $\log C$; and also of the precision of the observations, on the assumption that the distances of the observational points from the straight line represent errors of observation. The precision of the position of the line involves the precision of the adjusted values of capacity, and also the precision of the coefficient of the equation of adjustment. The method of computation, given below, is also the method employed in various other computations of precision, the results of which appear in later chapters.

Each logarithmic plot, corresponding to an observational series, was treated separately. The distance of each plotted observational point from the representative straight line, in a direction parallel to the axis of $\log C$, was measured. This distance, interpreted by the scale of the section paper, gives the logarithm of the ratio between an observed capacity and the corresponding adjusted capacity. By using a strip of the section paper as measuring scale, it was possible to read the ratio directly. It was also possible, without computation, and as a simple matter of reading, to subtract unity from the ratio and multiply the remainder by 100, thus recording directly the residual, or observational error, as a per cent of the quantity measured. The facility of this operation determined the estimation of all errors in percentage.

From the residuals thus obtained, probable errors were computed by the following approximate formulas, in which m is the number of the residuals and [v] is the sum of the residuals, irrespective of sign:

Probable error of an observation =

$$0.845 \frac{[v]}{\sqrt{m(m-1)}}$$

Probable error of adjusted capacities =

$$0.845 \frac{[v]}{m\sqrt{m-1}}$$

Table 12 contains the computed probable errors for all those series, 82 in number, in which the number of observations is not less than 4. For a smaller number of observations it was possible so to frame adjusting equations as to leave no residuals; and although this was not done, the propriety of applying the computation to such cases was not evident.

The arithmetical mean of the 82 values of probable error for adjusted capacities is ±2.50 per cent. The corresponding mean for observed capacities is ±8.80 per cent. Another measure of the precision of the observations, collectively, is the arithmetical mean, irrespective of sign, of all the residuals (966 in number) involved in the 82 series. That mean is 11.5 per cent.

While these estimates of precision are computed specifically for capacities or loads, the sources of the errors are not restricted to the observations of loads but include also the observations of slope and discharge. With use of the same diagrams it would be possible to consider slope as a function of capacity and compute the probable errors of slope determinations. The relations are such that, within any series, the probable error of slope, considered as a percentage, is less than the probable error of capacity.

The residuals within a series are, as a rule, relatively great for the lower slopes; but this is true only when the residuals are considered as fractional parts of the capacity values to which they pertain. If the residuals be measured in the unit of capacity, then they are relatively great for the higher slopes. The gradation of precision in relation to slope was discussed with some care, and an elaborate system of weights was prepared for the adjusted values of capacity. While these weights were of service in connection with various combinations afterward made, it has not seemed necessary to include them in the printed tables. It is to be understood, however, that the probable errors associated with each series in Table 12 apply to the values of capacity as a group, the probable errors (in per cent) of the smaller values being relatively great and those of the larger values relatively small.

The residuals represent chiefly the errors of observation, but they include also errors introduced in the process of adjustment. To whatever extent the formula of adjustment misrepresents the actual relation between the variables, to whatever extent the assigned values of σ are inaccurate, and to whatever extent the representative lines of the plot are misplaced, factors of error are introduced which tend to increase the residuals. The estimates of probable error of observations are therefore larger than they would be if the methods of adjustment were perfect.

The observations giving large percentage residuals were, as a class, treated in the graphic adjustments as of relatively low weight; but in the computations of probable error they were treated as of equal weight. The estimates of probable error, and their average values, are larger than they would be if computed with regard to weights. The influence of this factor can not be definitely evaluated, but ratios brought out in the discussion of residuals for the assignment of weights indicate that it has some importance. It is thought that the average probable error of the adjusted values may be as low as ±2.0 per cent, and that of the observations as low as ±7.0 per cent.

On the other hand, the computations take account only of the discrepancies revealed by comparing observations of the same series and do not cover such discrepancies as exist between one series and another. The estimates of probable error are smaller than they would be if both classes of discrepancies were included. This matter receives further consideration in Chapters V and VI.

DUTY.

The duty of water traction, as defined by the units adopted for this paper, is the capacity in grams per second for each cubic foot per second of discharge, and its formula is $U=\frac{C}{Q}$. The duty corresponding to each adjusted capacity has been computed, and the values appear in Table 12.

It is sometimes desirable to treat duty as the ratio which the mass of the load, or capacity, bears to the mass of the carrier. To obtain the value of duty as a ratio of masses the corresponding value of U should be divided by 28,350, the number of grams in a cubic foot of water.

It is sometimes desirable to treat duty as a volume of débris, including voids—that is, as the space occupied by débris as a deposit, either before or after transportation. In such cases the American engineer commonly uses the cubic yard as a unit of volume and 24 hours as a unit of time. To obtain the approximate duty in cubic yards of débris per 24 hours, divide the duty in gm./sec. by 14. The exact value of the appropriate divisor depends on the specific gravity of the débris particles and on the percentage of voids in the débris aggregate.

EFFICIENCY.

The measure of efficiency, as defined on page 36, is $E=\frac{C}{QS}$. The computed efficiencies are tabulated in Table 12, along with the adjusted capacities and duties.

TABLE 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency.*

[Gr., grade of débris; w, width of experiment trough in feet; Q, discharge in cubic feet per second; S, slope of channel bed, in per cent; C, capacity for stream traction, in grams per second; U, duty of water for traction, $=\frac{C}{Q}$; E, efficiency of current, $=\frac{C}{QS}$.]

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	w	Q	S	C	U	E	Adjusted data.	Observation.
(A)	0.66	0.093	1.2	23.0	247	206		
			1.4	32.3	347	248		
			1.6	42.6	458	286		
			1.8	53.5	576	320		
			2.0	65.5	704	352		
			2.2	78.0	840	382		
(A)	.66	.182	.7	18.7	103	147		
			.8	25.0	137	171		
			.9	32.0	176	196		
			1.0	39.5	217	217		
			1.2	56.3	309	257		
			1.4	75.0	412	294		
			1.6	96.0	528	330		
			1.8	119	654	363		
(A)	.66	.545	.5	49.8	91.4	183		
			.6	66.0	121	202		
			.7	83.0	152	217		
			.8	101	185	231		
			.9	120	220	244		
			1.0	140	257	257		
			1.2	184	358	282		
(A)	1.00	.182	.5	8.2	45.1	90.2		
			.6	12.5	68.6	114		
			.7	17.6	95.7	137		
			.8	23.5	129	161		
			.9	30.0	165	183		
			1.0	37.5	206	206		
			1.2	54.5	300	250		
			1.4	74.0	407	291		
			1.6	97.0	534	334		
			1.8	122	670	372		
			2.0	149	819	410		
			2.2	179	984	447		
(A)	1.00	.363	.4	17.0	46.8	117		
			.5	26.9	74.1	148		
			.6	38.2	105	175		
			.7	51.8	143	204		
			.8	66	182	228		
			.9	83	229	254		
			1.0	100	276	276		
			1.2	140	386	322		
			1.4	185	510	364		
			1.6	235	648	405		
			1.8	290	799	443		
(A)	1.00	.734	.4	42.5	58.0	145		
			.5	65	88.6	177		
			.6	91	124	207		
			.7	121	165	236		
			.8	154	210	262		
			.9	191	260	289		
			1.0	231	315	315		
			1.2	320	436	363		
(A)	1.32	.182	.5	7.0	38.5	77	1.6	5.2
			.6	11.2	61.6	103		
			.7	16.3	89.6	127		
			.8	22.3	122	152		
			.9	29.1	160	178		
			1.0	36.8	202	202		
			1.2	54.3	298	248		
			1.4	74.8	411	294		
			1.6	98	538	336		

TABLE 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	w	Q	S	C	U	E	Adjusted data.	Observation.
(A)	1.32	0.182	1.8	124	681	378	1.6	5.2
			2.0	152	835	418		
			2.2	183	1,010	459		
(A)	1.32	.363	.2	3.6	9.9	49.6	2.3	7.6
			.3	10.5	28.9	96.3		
			.4	19.5	53.7	134		
			.5	30.2	83.2	166		
			.6	42.6	117	195		
			.7	56.0	154	220		
			.8	71	196	245		
			.9	87	240	267		
			1.0	104	287	287		
			1.2	142	391	326		
			1.4	183	504	360		
			1.6	227	626	391		
			1.8	276	760	422		
			2.0	328	904	452		
(A)	1.32	.734	.3	27.3	37.2	124	2.3	7.2
			.4	48.2	65.6	164		
			.5	73.5	100	200		
			.6	103	140	233		
			.7	135	184	263		
			.8	170	232	290		
			.9	219	285	317		
			1.0	250	341	341		
			1.2	344	469	391		
			1.4	445	606	433		
(A)	1.96	.363	.4	12.6	34.7	86.8	2.6	9.4
			.5	22.4	61.7	123		
			.6	34.0	93.7	156		
			.7	47.3	130	186		
			.8	72.2	171	214		
			.9	79	218	242		
			1.9	96	264	265		
			1.2	136	375	312		
			1.4	178	490	350		
			1.6	227	625	390		
			1.8	278	766	425		
			2.0	335	923	462		
(A)	1.96	.734	.2	11.2	15.3	76.5	3.4	10.9
			.3	29.5	40.2	134		
			.4	52	70.8	177		
			.5	78	106	212		
			.6	105	143	238		
			.7	136	185	264		
			.8	169	230	288		
			.9	204	278	309		
			1.0	240	327	327		
			1.2	320	436	363		
(A)	1.96	1.119	.4	100	89.4	224	3.9	12.3
			.5	138	123	246		
			.6	180	161	268		
			.7	222	198	283		
			.8	266	238	298		
			.9	311	278	309		
			1.0	359	321	321		
(B)	.23	.093	.8	2.8	30.1	37.5	1.2	2.6
			.9	5.3	57.0	63.3		
			1.0	7.8	83.9	83.9		
			1.2	12.5	134	112		
			1.4	17.1	184	131		
			1.6	21.6	232	145		
			1.8	26.1	281	156		
			2.0	30.5	328	164		
			2.2	39.4	375	170		
(B)	.23	.182	.7	3.3	18.1	25.9		
			.8	6.7	36.8	46.0		
			.9	10.0	55.0	61.1		
			1.0	13.3	73.1	73.1		
			1.2	20.0	110	91.5		
			1.4	26.6	146	104		
			1.6	33.2	182	114		
			1.8	39.9	219	122		
(B)	.44	.093	.7	4.6	49.5		2.0	4.9
			.8	7.4	79.6			
			.9	10.2	110			
			1.0	13.2	142			
			1.2	19.5	210			
			1.4	26.2	282			
			1.6	33.0	355			
			1.8	40.0	430			
			2.0	47.2	508			
			2.2	54.7	588			
			2.4	62.0	667			
			2.6	70	753			

Table 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	*w*	*Q*	*S*	*C*	*V*	*E*	Adjusted data.	Observation.
(B)	0.44	0.182	0.5	7.7	42.3	84.6	0.9	2.1
			.6	11.0	60.5	101		
			.7	14.9	81.9	117		
			.8	19.0	104	130		
			.9	23.7	130	144		
			1.0	28.7	158	158		
			1.2	40.0	220	193		
			1.4	52.7	290	207		
			1.6	66	363	229		
			1.8	81	445	247		
(B)	.66	.093	.7	4.3	46.2	66.0	2.9	9.7
			.8	6.2	66.7	83.4		
			.9	8.4	90.3	100		
			1.0	10.8	116	116		
			1.2	16.3	175	146		
			1.4	22.9	247	176		
			1.6	30.0	323	202		
			1.8	38.0	409	227		
			2.0	46.5	500	250		
			2.2	56.0	602	274		
			2.4	66.0	710	296		
			2.6	76.5	823	316		
			2.8	88.0	946	338		
			3.0	100	1,080	360		
(B)	.66	.182	.3	2.8	15.4	51.3	1.8	9.7
			.4	5.5	30.2	75.5		
			.5	8.9	48.9	97.9		
			.6	12.8	70.4	117		
			.7	17.3	95.1	136		
			.8	22.2	122	152		
			.9	27.6	152	169		
			1.0	33.5	184	184		
			1.2	46.7	257	214		
			1.4	61.4	338	241		
			1.6	78	429	268		
			1.8	96	528	293		
			2.0	113	621	310		
			2.2	134	736	335		
			2.4	156	858	357		
			2.6	179	984	378		
			2.8	202	1,110	397		
			3.0	228	1,250	413		
			3.2	255	1,400	438		
			3.4	281	1,540	453		
			3.6	310	1,700	472		
			3.8	340	1,870	492		
			4.0	371	2,040	510		
			4.2	402	2,210	526		
(B)	.66	.363	.5	26.0	71.6	143	1.4	5.4
			.6	35.2	97	162		
			.7	45.6	126	180		
			.8	56.9	157	196		
			.9	68.3	188	209		
			1.0	81	223	223		
			1.2	107	295	246		
			1.4	137	378	270		
			1.6	168	463	289		
			1.8	200	551	306		
			2.0	234	644	322		
(B)	.66	.545	.2	7.9	14.5	72.5	3.6	13.0
			.3	17.4	31.9	106		
			.4	28.7	52.6	132		
			.5	41.3	75.8	152		
			.6	55.0	101	168		
			.7	70	128	183		
			.8	86	158	198		
			.9	102	187	208		
			1.0	120	220	220		
			1.2	158	290	242		
			1.4	198	363	259		
			1.6	240	440	275		
			1.8	284	521	289		
			2.0	330	606	303		
(B)	1.00	.182	.5	7.3	40.1	80.2	1.1	3.4
			.6	10.8	59.4	99.0		
			.7	15.0	82.4	118		
			.8	19.5	107	134		
			.9	24.6	135	150		
			1.0	30.1	165	165		
			1.2	42.8	235	179		
			1.4	57	313	223		
			1.6	73	401	259		
			1.8	90	495	275		
			2.0	108	594	297		
			2.2	129	709	322		
			2.4	150	824	343		

TABLE 12. *Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(B)	1.00	0.182	2.6	173	954	366	1.1	3.4
			2.8	197	1,080	386		
			3.0	224	1,230	410		
(B)	1.00	.363	.2	3.7	10.2	51.0	3.6	16.5
			.3	9.4	25.9	86.3		
			.4	16.6	45.8	114		
			.5	25.4	70	140		
			.6	35.3	97.2	162		
			.7	46.2	127	181		
			.8	58.5	161	201		
			.9	71	196	218		
			1.0	85	234	234		
			1.2	116	320	267		
			1.4	149	411	293		
			1.6	186	512	320		
			1.8	225	620	344		
			2.0	266	732	366		
			2.2	310	854	388		
			2.4	356	981	419		
(B)	1.00	.545	.8	99	182	228	1.9	6.0
			.9	120	220	244		
			1.0	143	262	262		
			1.2	193	354	295		
			1.4	247	453	323		
			1.6	305	560	350		
			1.8	368	675	375		
			2.0	435	798	399		
			2.2	505	927	421		
(B)	1.00	.734	.2	11.0	15.0	75	2.8	11.4
			.3	25.0	34.1	114		
			.4	42.8	58.3	146		
			.5	63	86	172		
			.6	86	117	195		
			.7	110	150	214		
			.8	138	188	235		
			.9	168	229	254		
			1.0	199	271	271		
			1.2	268	365	304		
			1.4	344	469	335		
			1.6	422	575	359		
			1.8	507	691	384		
(B)	1.32	.182	.4	3.7	20.3	50.8	1.6	5.4
			.5	6.6	36.3	72.6		
			.6	10.1	55.5	92.5		
			.7	14.1	77.5	111		
			.8	18.7	103	129		
			.9	23.8	131	146		
			1.0	29.3	161	161		
			1.2	42.0	231	176		
			1.4	55.8	307	219		
			1.6	71	390	244		
			1.8	88	484	269		
			2.0	105	577	288		
			2.2	124	682	310		
			2.4	144	791	330		
			2.6	166	912	351		
(B)	1.32	.363	.3	6.9	....	....	2.4	10.9
			.4	13.6	37.5	93.8		
			.5	21.8	60.1	120		
			.6	31.2	86.0	143		
			.7	41.9	115	164		
			.8	53.1	146	182		
			.9	65.5	180	200		
			1.0	79	218	218		
			1.2	109	300	250		
			1.4	141	389	278		
			1.6	177	488	305		
			1.8	215	592	329		
			2.0	255	702	351		
			2.2	297	818	372		
(B)	1.32	.545	.5	39.8	73	146	4.1	18.3
			.6	56	103	172		
			.7	75	138	197		
			.8	95	174	218		
			.9	116	213	237		
			1.0	140	257	257		
			1.2	191	351	292		
			1.4	248	455	325		
			1.6	310	569	355		
			1.8	375	688	382		
(B)	1.32	.734	.3	21.7	29.6	98.7	2.1	9.7
			.4	39.0	53.1	133		
			.5	59.5	81.0	162		
			.6	83	113	188		
			.7	110	150	211		

Table 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(B)	**1.32**	0.734	0.8	139	189	236	2.1	9.7
			.9	170	232	258		
			1.0	204	278	278		
			1.2	279	380	317		
			1.4	361	492	351		
			1.6	450	613	383		
			1.8	545	742	412		
(B)	**1.96**	.363	.4	7.7	21.2	50.3	3.9	15.5
			.5	14.3	39.4	76.8		
			.6	22.4	61.7	103		
			.7	32.0	88.2	126		
			.8	43.0	118	148		
			.9	54.8	151	168		
			1.0	67.6	186	186		
			1.2	97	267	222		
			1.4	130	358	256		
			1.6	167	460	287		
			1.8	208	573	318		
			2.0	253	697	348		
			2.2	300	826	375		
(B)	**1.96**	.545	.5	29.8	54.7	109	2.9	11.3
			.6	44.2	81.1	135		
			.7	60.5	111	159		
			.8	79	145	181		
			.9	98	180	200		
			1.0	120	220	220		
			1.2	168	308	257		
			1.4	221	406	290		
			1.6	282	517	323		
			1.8	345	633	352		
(B)	**1.96**	.734	.3	18.6	25.3	84.3	4.1	17.1
			.4	35.8	48.8	122		
			.5	56.0	76.3	155		
			.6	78.5	107	178		
			.7	103	140	200		
			.8	130	177	221		
			.9	158	215	239		
			1.0	190	259	259		
			1.2	257	350	292		
			1.4	330	450	322		
			1.6	407	554	346		
			1.8	488	665	369		
			2.0	575	783	392		
(B)	1.96	**1.119**	.2	13.4	12.0	60	5.4	24.1
			.3	36.1	32.3	108		
			.4	65.0	58.1	145		
			.5	98	87.5	175		
			.6	135	121	202		
			.7	175	156	223		
			.8	218	195	241		
			.9	263	235	261		
			1.0	313	280	280		
			1.2	417	373	311		
(C)	.44	.093	.6	2.3	24.7	41.2	3.3	10.1
			.7	4.1	44.1	63.0		
			.8	6.1	65.6	82.0		
			.9	8.4	90.4	100		
			1.0	10.9	117	117		
			1.2	16.4	176	147		
			1.4	22.6	243	174		
			1.6	29.4	316	197		
			1.8	36.6	394	219		
			2.0	44.2	475	238		
			2.2	52.3	562	255		
(C)	**.44**	**.182**	.6	8.7	47.8	79.7	2.3	6.1
			.7	12.1	66.5	95		
			.8	15.9	87.4	109		
			.9	20.1	110	122		
			1.0	24.7	136	136		
			1.2	34.3	188	157		
			1.4	45.3	249	178		
			1.6	57.2	314	196		
			1.8	70	385	214		
			2.0	84	462	231		
			2.2	98	538	244		
(C)	.66	.093	.5	3.3	35.5	71.0	1.7	6.8
			.6	5.0	53.8	89.7		
			.7	6.9	74.2	106		
			.8	9.0	96.8	121		
			.9	11.3	121	134		
			1.0	13.8	148	148		
			1.2	19.4	209	174		
			1.4	25.7	276	197		
			1.6	32.4	348	217		
			1.8	39.7	427	237		

TABLE 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(C)	0.66	0.093	2.0	47.5	511	256	1.7	6.8
			2.2	56	602	274		
			2.4	65	699	291		
			2.6	74	796	306		
			2.8	84	904	323		
			3	95	1,020	340		
			3.2	105	1,130	353		
			3.4	117	1,260	371		
			3.6	128	1,380	384		
			3.8	140	1,510	398		
			4	153	1,650	412		
			4.2	166	1,780	424		
(C)	.66	.182	.3	3	16.5	55	1.2	5.8
			.4	5.7	31.3	75.8		
			.5	9	49.5	99		
			.6	12.9	70.9	118		
			.7	17.1	94	134		
			.8	21.8	120	150		
			.9	26.7	147	163		
			1	32.1	176	176		
			1.2	44.1	242	202		
			1.4	57	313	223		
			1.6	71	390	244		
			1.8	87	478	265		
			2	102	560	280		
			2.2	120	659	299		
			2.4	138	758	316		
			2.6	157	863	332		
			2.8	177	892	347		
			3	198	1,090	363		
			3.2	219	1,200	375		
			3.4	241	1,320	388		
			3.6	266	1,460	406		
			3.8	289	1,590	419		
(C)	.66	.363	.4	16.5	45.5	114	1.8	9.0
			.5	23.3	64.2	128		
			.6	31.9	87.9	146		
			.7	41.2	113	161		
			.8	51.1	141	176		
			.9	62	171	190		
			1	73	201	201		
			1.2	98	270	225		
			1.4	124	342	244		
			1.6	152	419	262		
			1.8	183	514	280		
			2	215	592	296		
			2.2	248	683	310		
			2.4	283	780	325		
			2.6	320	882	339		
(C)	.66	.545	.2	6.6	12.1	60.5	2.1	10.1
			.3	14.8	27.2	90.7		
			.4	24.8	45.5	114		
			.5	36.5	67.0	134		
			.6	49.2	90.2	150		
			.7	63.3	116	166		
			.8	78.5	144	180		
			.9	95	174	193		
			1	112	205	205		
			1.2	150	275	229		
			1.4	190	349	249		
			1.6	233	427	267		
			1.8	280	514	285		
			2	328	602	301		
			2.2	380	697	317		
(C)	.66	.734	.5	51	69.5	139	3.8	8.5
			.6	68	93	154		
			.7	87	118	169		
			.8	107	146	182		
			.9	129	176	196		
			1	152	207	207		
(C)	1.00	.182	.4	4.5	24.7	61.8	1	4.4
			.5	7.6	41.8	83.6		
			.6	11.4	62.6	104		
			.7	15.6	85.8	123		
			.8	20.4	112	140		
			.9	25.6	141	157		
			1	31.2	171	171		
			1.2	44	242	202		
			1.4	57.7	317	226		
			1.6	72	396	247		
			1.8	90	495	275		
			2	106	582	291		
			2.2	125	686	312		
			2.4	145	797	332		
			2.6	166	912	351		
			2.8	189	1,040	372		

TABLE 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(C)	1.00	0.363	0.2	3.3	9.1	45.5	1.2	6.2
			.3	9.6	26.4	88		
			.4	17.5	48.2	120		
			.5	26.6	73.3	147		
			.6	36.6	101	168		
			.7	47.5	131	187		
			.8	59	163	204		
			.9	72	198	220		
			1	85	234	234		
			1.2	113	311	259		
			1.4	143	394	281		
			1.6	175	482	301		
			1.8	210	579	322		
			2	245	675	338		
			2.2	281	774	352		
			2.4	320	882	367		
			2.6	360	992	381		
			2.8	401	1,100	393		
(C)	1.00	.545	.5	48.2	88.4	177	1.1	5.5
			.6	64.9	119	198		
			.7	82	150	214		
			.8	100	183	229		
			.9	119	218	242		
			1.0	140	257	257		
			1.2	183	336	280		
			1.4	228	418	299		
			1.6	275	504	315		
			1.8	326	598	332		
			2.0	377	692	346		
			2.2	430	789	359		
(C)	1.00	.734	.2	12.5	17.0	85	7.8	37.7
			.3	27.3	37.2	124		
			.4	44.2	60.2	150		
			.5	63.2	86.2	172		
			.6	84	114	190		
			.7	106	144	206		
			.8	130	177	221		
			.9	155	211	234		
			1.0	180	245	245		
			1.2	235	320	267		
			1.4	294	401	286		
			1.6	352	480	300		
			1.8	416	567	315		
			2.0	483	658	329		
			2.2	550	750	341		
(C)	1.00	1.119	.5	96	85.8	172	2.3	5.1
			.6	128	114	190		
			.7	162	145	207		
			.8	198	177	221		
			.9	236	211	234		
			1.0	276	247	247		
			1.2	361	323	269		
			1.4	451	403	288		
(C)	1.32	.182	.6	5.6	30.8	51.3	2.4	8.4
			.7	8.7	47.8	68.3		
			.8	12.3	67.6	84.5		
			.9	16.6	91.2	101		
			1.0	21.4	118	118		
			1.2	32.7	180	150		
			1.4	46.5	256	183		
			1.6	62	341	213		
			1.8	80	440	244		
			2.0	99	544	272		
			2.2	120	659	299		
			2.4	144	791	329		
(C)	1.32	.363	.3	6.4	17.6	58.7	1.2	5.5
			.4	13.6	37.5	93.8		
			.5	22.1	60.9	122		
			.6	31.9	87.9	146		
			.7	42.2	116	166		
			.8	53.8	148	185		
			.9	66	182	202		
			1.0	79	218	218		
			1.2	105	289	241		
			1.4	135	372	266		
			1.6	166	458	286		
			1.8	199	548	304		
			2.0	233	642	321		
			2.2	270	744	338		
			2.4	307	846	352		
(C)	1.32	.545	.6	56.3	103	172	1.8	8.5
			.7	73.3	134	191		
			.8	91	167	209		
			.9	109	200	222		
			1.0	129	237	237		
			1.2	171	314	262		

TABLE 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(C)	1.32	0.345	1.4	215	395	282	1.8	8.3
			1.6	263	483	302		
			1.8	312	573	318		
			2.0	362	664	332		
			2.2	415	762	346		
			2.4	470	862	359		
(C)	1.32	.734	.2	9.3	12.7	63.5	2.2	9.0
			.3	25.0	34.1	114		
			.4	43.2	58.9	147		
			.5	63.8	86.9	174		
			.6	86	117	195		
			.7	109	148	211		
			.8	133	181	226		
			.9	160	218	242		
			1.0	187	255	255		
			1.2	243	331	276		
			1.4	304	414	296		
			1.6	367	500	312		
			1.8	432	589	327		
			2.0	500	681	340		
			2.2	570	777	353		
(C)	1.96	.363	.5	10.5	28.9	57.8	3.5	15.5
			.6	17.8	49.0	81.7		
			.7	26.5	73.0	104		
			.8	36.6	101	126		
			.9	47.9	132	147		
			1.0	60.0	165	165		
			1.2	88	242	202		
			1.4	119	328	234		
			1.6	154	424	265		
			1.8	193	532	295		
			2.0	235	648	324		
			2.2	280	771	350		
(C)	1.96	.545	.5	25.7	47.2	94.4	2.0	7.0
			.6	39.3	72.1	120		
			.7	55.0	101	144		
			.8	72	132	165		
			.9	91	167	186		
			1.0	111	204	204		
			1.2	156	286	238		
			1.4	205	376	268		
			1.6	259	475	297		
			1.8	316	580	322		
			2.0	375	688	344		
			2.2	440	808	367		
(C)	1.96	.734	.4	34.0	46.3	116	2.8	13.2
			.5	55	74.9	150		
			.6	78	106	177		
			.7	103	140	200		
			.8	131	178	222		
			.9	160	218	242		
			1.0	190	259	259		
			1.2	255	347	289		
			1.4	323	410	314		
			1.6	394	537	336		
(C)	1.96	1.119	.5	88	78.7	157	2.2	8.9
			.6	130	116	193		
			.7	177	158	226		
			.8	228	204	255		
			.9	283	253	281		
			1.0	343	307	307		
			1.2	480	429	358		
(D)	.66	.093	.6	2.7	29.0	48.4	2.6	8.1
			.7	3.9	41.9	59.9		
			.8	5.4	58.1	72.5		
			.9	7.1	76.4	84.9		
			1.0	9.1	97.9	97.9		
			1.2	13.5	145	121		
			1.4	18.6	200	143		
			1.6	24.7	266	166		
			1.8	31.4	338	188		
			2.0	38.5	414	207		
			2.2	46.3	498	226		
			2.4	55.2	594	248		
			2.6	64.3	692	266		
(D)	.66	.182	.4	4.7	25.8	64.5	4.2	15.2
			.5	7.7	42.3	84.6		
			.6	11.3	62.1	104		
			.7	15.3	84.1	120		
			.8	19.7	108	135		
			.9	24.6	135	150		
			1.0	29.8	164	164		
			1.2	41.0	225	188		
			1.4	53.4	293	209		

Table 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of -	
Gr.	w	Q	S	C	U	E	Adjusted data.	Observation.
(D)	0.66	0.182	1.6	67	368	230	4.2	15.2
			1.8	82	450	250		
			2.0	98	538	269		
			2.2	114	626	284		
			2.4	132	726	302		
			2.6	150	824	317		
(D)	.66	.545	.2	4.7	8.5	42.5	3.4	15.3
			.3	11.7	21.5	71.6		
			.4	20.7	38.0	95		
			.5	31.2	57.2	114		
			.6	43.1	79.1	132		
			.7	56.2	103	147		
			.8	70.2	129	161		
			.9	86	158	176		
			1.0	101	185	185		
			1.2	137	251	209		
			1.4	175	321	229		
			1.6	217	398	249		
			1.8	261	479	266		
			2.0	308	568	284		
			2.2	357	655	298		
(D)	1.00	.182	.7	11.3	62.1	88.7	2.5	9.1
			.8	15.1	83	104		
			.9	19.2	106	118		
			1.0	24.0	132	132		
			1.2	34.5	190	158		
			1.4	46.4	255	182		
			1.6	59.8	329	206		
			1.8	74	407	226		
			2.0	90	495	248		
			2.2	106	582	264		
			2.4	124	682	284		
			2.6	144	792	304		
			2.8	164	902	324		
(D)	1.00	.363	.3	6.9	19.0	63	3.3	13.2
			.4	13.2	36.4	91.0		
			.5	20.9	57.6	115		
			.6	29.6	81.6	136		
			.7	39.0	107	153		
			.8	49.6	137	171		
			.9	61	168	187		
			1.0	73	201	201		
			1.2	99	273	228		
			1.4	127	350	250		
			1.6	158	435	272		
			1.8	190	524	291		
			2.0	225	620	310		
			2.2	261	819	327		
			2.4	299	824	343		
(D)	1.00	.545	.5	27.6	50.6	101	1.2	3.9
			.6	40.2	73.8	123		
			.7	55.0	101	144		
			.8	71	130	162		
			.9	89	163	181		
			1.0	108	198	198		
			1.2	152	279	232		
			1.4	201	369	264		
			1.6	257	472	295		
			1.8	317	582	323		
			2.0	382	700	350		
(D)	1.00	.734	.2	6.9	9.4	47.0	2.5	11.5
			.3	17.5	23.8	79.3		
			.4	31.0	42.2	106		
			.5	47.0	64.0	128		
			.6	65.0	88.6	148		
			.7	85	116	166		
			.8	106	144	180		
			.9	129	176	196		
			1.0	153	208	208		
			1.2	208	282	236		
			1.4	268	365	361		
			1.6	332	452	283		
			1.8	388	542	302		
(D)	1.32	.363	.5	11.9	32.8	65.6	7.0	24.3
			.6	18.8	50.9	84.8		
			.7	27.0	74.4	106		
			.8	36.6	101	139		
			.9	47.2	130	144		
			1.0	59.2	163	163		
			1.2	87	240	200		
			1.4	118	325	232		
			1.6	154	424	265		
			1.8	194	534	297		
			2.0	237	653	326		

TABLE 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	w	Q	S	C	U	F	Adjusted data.	Observation.
(D)	1.32	0.734	0.3	10.2	13.9	46.3	5.3	21.4
			.4	20.9	28.5	71.2		
			.5	34.0	46.3	92.6		
			.6	49.2	67.0	112		
			.7	67	91.3	130		
			.8	87	118	148		
			.9	108	147	163		
			1.0	131	178	178		
			1.2	185	252	210		
(E)	.66	.363	1.0	24.8	68.3	68.3	0.9	2.1
			1.2	36.2	99.7	83.1		
			1.4	49.4	136	97.2		
(E)	.66	.734	1.0	40.0	54.5	54.5		
			1.2	59.0	80.4	67.0		
			1.4	82	112	80		
			1.6	108	147	92		
(E)	1.00	.182	.4	2.4	13.2	33.0	1.9	5.0
			.5	3.8	20.9	41.8		
			.6	5.5	30.4	50.7		
			.7	7.4	40.6	58.0		
			.8	9.6	52.7	65.0		
			.9	12.0	66.0	73.3		
			1.0	14.8	81.4	81.4		
			1.2	20.7	114	95		
			1.4	27.6	152	108		
			1.6	35.3	194	121		
			1.8	43.5	239	133		
			2.0	52.5	288	144		
			2.2	62.4	343	156		
			2.4	73	401	167		
			2.6	84	461	177		
			2.8	96	527	188		
(E)	1.00	.363	.2	1.3	3.6	18.0	5.1	14.6
			.3	3.3	9.1	30.3		
			.4	6.0	16.5	41.2		
			.5	9.2	25.3	50.6		
			.6	13.1	36.1	60.1		
			.7	17.5	48.2	68.9		
			.8	22.5	62.0	77.5		
			.9	28.0	77.2	85.8		
			1.0	33.8	93.1	93.1		
			1.2	47.2	130	108		
			1.4	62.0	171	122		
			1.6	78.5	216	135		
			1.8	96	264	147		
			2.0	115	317	158		
			2.2	137	378	172		
			2.4	159	438	182		
(E)	1.00	.734	.2	4.2	5.7	28.5	5.0	19.5
			.3	9.1	12.4	41.3		
			.4	15.2	20.7	51.8		
			.5	22.4	30.5	61.0		
			.6	30.8	42.0	70.0		
			.7	40.0	54.5	77.9		
			.8	49.8	67.8	84.8		
			.9	60.5	72.4	91.6		
			1.0	72.0	98.1	98.1		
			1.2	98	134	112		
			1.4	126	172	123		
			1.6	156	213	133		
			1.8	188	256	142		
			2.0	222	302	151		
(E)	1.00	1.119	.5	44	39.3	76.6	3.2	6.4
			.6	60	54	89		
			.7	77	69	98		
			.8	97	87	108		
			.9	117	105	117		
			1.0	138	123	123		
			1.2	188	168	140		
			1.4	242	216	154		
(E)	1.32	.363	.6	15.3	42.2	70.3		
			.7	20.3	55.9	79.9		
			.8	25.4	70.0	87.5		
			.9	30.7	84.6	94.0		
			1.0	36.3	100	100		
			1.2	49.3	136	113		
			1.4	63.5	175	125		
			1.6	78.8	217	136		
			1.8	95	262	145		
			2.0	112	309	154		
(E)	1.32	.734	.5	24.7	33.7	67.4		
			.6	33.0	45.0	75.0		
			.7	42.0	57.2	81.7		
			.8	51.7	70.4	88.0		
			.9	62	84.5	93.9		
			1.0	73	99.5	99.5		
			1.2	97	132	110		

Table 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(E)	1.32	1.119	0.6	49.4	44.2	73.7	1.8	3.6
			.7	65.0	58.1	83.0		
			.8	82.5	73.7	92.1		
			.9	102	91.1	101		
			1.0	123	110	110		
			1.2	171	153	128		
(F)	.66	.182	1.2	9.3	51.0	42.5	.8	1.7
			1.4	13.7	75.3	53.8		
			1.6	18.9	104	65.0		
			1.8	24.7	136	75.6		
			2.0	31.4	172	86.0		
			2.2	38.7	213	96.8		
			2.4	46.8	257	107		
			2.6	55.7	306	118		
(F)	.66	.363	1.0	20.5	56.5	56.5	2.3	4.6
			1.2	29.9	82.4	68.7		
			1.4	41.0	113	80.8		
			1.6	53.2	147	91.9		
			1.8	67.0	185	103		
			2.0	81.5	225	112		
(F)	.66	.734	.8	31.6	43.0	47.8	.4	.8
			1.0	39.0	53.2	53.2		
			1.2	55.3	75.3	62.8		
			1.4	73.0	99.5	71.0		
			1.6	93.5	127	79.4		
			1.8	115	157	87.2		
(F)	1.00	.182	1.2	4.2	23.1	17.6		
			1.4	7.3	40.1	28.6		
			1.6	11.3	62.1	38.8		
			1.8	16.4	90.1	50.0		
			2.0	22.5	124	62.0		
			2.2	29.8	164	74.6		
			2.4	38.2	210	87.5		
			2.6	47.7	262	101		
(F)	1.00	.363	.8	7.4	20.4	25.5	2.0	4.8
			.9	10.5	28.9	32.1		
			1.0	14.0	38.6	38.6		
			1.2	22.8	62.8	52.3		
			1.4	33.4	92.0	65.7		
			1.6	46.0	127	79.4		
			1.8	60	165	91.7		
			2.0	76	209	104		
			2.2	94	259	118		
			2.4	112	309	129		
			2.6	133	367	141		
(F)	1.00	.734	.7	20.0	27.3	39.0	.5	1.0
			.8	27.3	37.2	46.5		
			.9	35.1	47.8	53.1		
			1.0	42.8	58.3	58.3		
			1.2	63	85.8	71.5		
			1.4	85	116	82.9		
			1.6	109	148	92.6		
			1.8	136	185	103		
(F)	1.00	1.119	.7	37.5	33.5	47.9	.9	1.8
			.8	51.0	45.6	57.0		
			.9	64.8	57.9	64.3		
			1.0	79.5	71.0	71.0		
			1.2	112	100	83.3		
			1.4	150	134	95.8		
			1.6	191	171	107		
			1.8	236	211	117		
(F)	1.32	.363	1.2	21.4	59.0	48.2	1.2	2.4
			1.4	31.0	85.4	61.0		
			1.6	41.5	114	71.3		
			1.8	53.0	146	81.1		
			2.0	66.0	182	91.0		
			2.2	80	220	100		
(F)	1.32	.734	.8	22.9	29.6	37.0	3.2	7.2
			.9	31.0	40.1	44.6		
			1.0	40.2	52.0	52.0		
			1.2	61.6	79.7	66.4		
			1.4	87.0	119	85.0		
			1.6	115	149	93.2		
(F)	1.32	1.119	.8	43.3	38.7	48.4	3.2	7.2
			.9	56.0	50.0	91.1		
			1.0	70.0	62.6	62.6		
			1.2	101	90.2	75.2		
			1.4	138	123	87.9		
			1.6	178	159	99.4		
			1.8	221	197	109		

Table 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of—	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(G)	0.66	0.363	1.0	8.5	23.4	23.4	2.2	5.8
			1.2	14.8	40.8	34.0		
			1.4	23.0	63.4	45.3		
			1.6	32.7	90.1	56.3		
			1.8	43.7	120	66.7		
			2.0	56.0	154	77.0		
(G)	.66	.734	.7	10.3	13.3	19.0	1.5	4.3
			.8	16.0	20.7	25.9		
			.9	22.8	29.5	32.8		
			1.0	30.4	39.3	39.3		
			1.2	48.3	62.5	52.1		
			1.4	69	89.2	63.7		
			1.6	93	127	79.4		
			1.8	120	155	86.2		
			2.0	149	193	96.5		
			2.2	181	234	106		
			2.4	216	280	117		
			2.6	253	327	126		
(G)	.66	1.119	.6	11.9	10.6	17.7	1.2	3.6
			.7	19.0	17.0	24.3		
			.8	27.7	24.7	30.9		
			.9	37.6	33.6	37.3		
			1.0	49.0	43.8	43.8		
			1.2	75.0	67.0	55.8		
			1.4	107	95.6	68.3		
			1.6	143	128	80.0		
			1.8	182	163	90.6		
			2.0	227	203	102		
			2.2	276	247	112		
			2.4	325	290	121		
			2.6	382	341	131		
(G)	1.00	.363	1.2	9.7	26.7	22.2	1.9	5.0
			1.4	16.3	44.9	35.0		
			1.6	24.4	67.2	42.0		
			1.8	34.1	94.0	52.2		
			2.0	45.2	125	62.5		
			2.2	57	157	71.4		
			2.4	71	196	81.7		
			2.6	86	237	91.2		
			2.8	102	281	100		
			3.0	120	331	110		
(G)	1.00	.734	.7	8.0	10.9	15.6	1.9	5.5
			.8	13.3	18.1	22.6		
			.9	19.5	26.6	29.6		
			1.0	26.9	36.6	36.6		
			1.2	44	60.0	50.0		
			1.4	65	88.6	63.3		
			1.6	89	121	75.6		
			1.8	115	157	87.8		
			2.0	145	198	99.0		
			2.2	177	241	110		
			2.4	212	289	120		
			2.6	249	339	130		
(G)	1.00	1.119	.6	13.5	12.1	20.1	4.3	13.6
			.7	22.7	20.3	29.0		
			.8	33.6	30.0	37.5		
			.9	46.0	41.1	45.6		
			1.0	61.0	54.4	54.4		
			1.2	92	82.2	68.5		
			1.4	128	114	81.5		
			1.6	171	153	95.6		
			1.8	217	194	108		
			2.0	268	239	120		
			2.2	321	287	130		
			2.4	380	340	142		
(G)	1.32	.363	1.8	18.1	49.5	27.7	2.4	4.8
			2.0	28.3	78.0	39.0		
			2.2	39.9	101	45.9		
			2.4	53.8	148	61.7		
			2.6	69.8	192	73.9		
			2.8	88.0	242	86.5		
			3.0	109	300	100		
			3.2	134	369	115		
(G)	1.32	.734	.8	7.9	10.8	13.5	2.2	5.8
			.9	12.8	17.4	19.3		
			1.0	18.9	25.8	25.8		
			1.2	33.8	46.1	38.4		
			1.4	52.0	70.8	50.6		
			1.6	74.0	101	63.2		
			1.8	98.0	134	75.4		
			2.0	125	170	85.0		
			2.2	155	211	95.9		
			2.4	187	255	106		
			2.6	222	303	117		
			2.8	260	354	126		

Table 12.—*Adjusted values of capacity, based on data of Table 4, with corresponding values of duty and efficiency*—Con.

Conditions.				Adjusted data.			Probable error (per cent) of	
Gr.	*w*	*Q*	*S*	*C*	*U*	*E*	Adjusted data.	Observation.
(G)	1.32	1.119	0.7	17.9	16.0	22.9	3.1	8.7
			.8	28.0	25.0	31.2		
			.9	39.5	35.3	38.1		
			1.0	52.2	46.6	46.6		
			1.2	81	72.4	60.3		
			1.4	115	103	73.6		
			1.6	153	137	85.6		
			1.8	194	173	96.2		
			2.0	238	213	106		
			2.2	285	255	116		
			2.4	335	299	125		
			2.6	387	346	133		
(H)	.66	.363	1.2	3.1	8.5	7.1	1.0	3.5
			1.4	6.9	19.0	13.6		
			1.6	12.4	34.2	21.4		
			1.8	19.4	53.5	29.7		
			2.0	28.0	77.1	38.6		
			2.2	38.1	105	47.8		
			2.4	49.8	137	57.1		
			2.6	63	174	66.9		
			2.8	78	215	76.8		
(H)	.66	.734	.8	4.5	6.8	8.5	1.6	4.9
			.9	8.2	12.4	13.8		
			1.0	12.8	19.4	19.4		
			1.2	24.6	37.3	31.1		
			1.4	39.2	59.4	42.4		
			1.6	57.0	86.4	54.0		
			1.8	77.0	117	65.0		
			2.0	100	152	76.0		
			2.2	125	189	85.9		
			2.4	151	229	95.6		
			2.6	181	274	105		
			2.8	213	323	115		
			3.0	246	373	126		
			3.2	282	427	133		
(H)	.66	1.119	.7	6.0	5.4	7.7		11.2
			.8	11.1	9.9	12.4	3.2	
			.9	17.6	15.7	17.4		
			1.0	25.2	22.5	22.5		
			1.2	43.5	38.8	32.3		
			1.4	65.3	58.3	41.6		
			1.6	91.0	81.3	50.8		
			1.8	120	107	59.5		
			2.0	152	136	68.0		
			2.2	186	166	75.5		
			2.4	223	199	83.0		
			2.6	263	235	90.4		

OBSERVATIONS ON DEPTH.

MODE OF ADJUSTMENT.

To adjust the observations of depth it is necessary to deal with their relations to another variable, and either slope or capacity might be used. The selection of the particular variable for comparison was a matter of convenience only, because adjustment to either one would bring the depth values into orderly relation to the adjusted values of the other also; but the question of convenience was not unimportant. A fairly thorough preliminary study was therefore made, in which the depth measurements for many series were plotted in relation, severally, to measurements of capacity and measurements of slope.

In figure 27 the horizontal scale is that of slope, the vertical of depth. The round dots represent observations made with grade (C), width 1.32 feet, and discharge 0.734 ft.^{3}/sec. Despite irregularities, the grouping suggests as the representative line some such curve as that drawn. On taking account of the physical con-

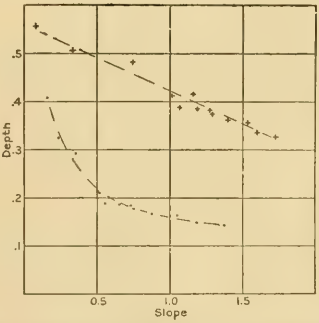

Figure 27. Observations of depth of current, in relation to slope, plotted as dots. The crosses show logarithms of the same depths and slopes.

ditions, it is evident that as the slope is flattened, the current is slowed and the depth increased, and that zero slope gives infinite depth. The theoretic curve, therefore, has an asymptote in the vertical line corresponding to zero slope. Similarly the depth is reduced by increase in slope but remains finite for very high slopes. The theoretic curve has as asymptote a horizontal line corresponding, exactly or approximately, with the (horizontal) line of zero depth. These asymptotes relate the curve $d=f(S)$ to the hyperbola. In the same figure, but with use of a different scale, are a series of crosses which show the same observations as they appear when plotted on logarithmic section paper. They are the plot of observations on $\log d=f_{\mathrm{I}}(\log S)$; and their arrangement suggests that the representative line may be straight.

Plots were made to show the relations of depth observations to associated capacity, and these also suggest the hyperbola and the straight line. If, however, the locus of $d=f_{\mathrm{II}}(C)$ is a hyperbola it differs materially from that of $d=f(S)$, for as depth increases and current slackens, capacity becomes zero when current reaches the value of competence, and depth is not then infinite. So the line of zero capacity is not an asymptote to the curve.

It is to be observed also that the representative lines for $\log d=f_{\mathrm{I}}(\log S)$ and $\log d=f_{\mathrm{IV}}(\log C)$ can not both be straight, for if they were there could be derived from them a straight line representing $\log C=f_{\mathrm{V}}(\log S)$, and it has already been found that that line is curved. It is, indeed, probable that neither of the logarithmic plots involving depth is straight; yet there are cogent practical reasons for assuming one or the other to be so. One reason is the very great convenience of the straight-line function, and another that the relatively small range of the depth data renders impracticable such a discussion of the curvature of logarithmic loci as was made in the case of capacity versus slope. Accordingly, the most orderly plots of $\log d=f_{\mathrm{I}}(\log S)$ and $\log d=f_{\mathrm{IV}}(\log C)$ were compared with special reference to curvature. For the function of $\log C$ the plots were found to indicate curvature in one direction only, while for the function of $\log S$ they indicated slight curvatures in both directions, with the straight line as an approximate mean. The function $\log d=f_{\mathrm{I}}(\log S)$ was accordingly selected for the adjustment of the depth observations; and the representative line on the logarithmic plot was assumed to be straight. In accordance with that assumption, the adopted formula of interpolation was

$$d=\frac{b'}{S^{n_1}} \quad \text{-------------} \quad (21)$$

with its logarithmic equivalent,

$$\log d=\log b'-n_1 \log S \quad \text{-------} \quad (22)$$

The coefficient b' is a depth, the depth corresponding to a slope of 1 per cent.

The data were all plotted on logarithmic section paper. The notation was made to distinguish depth measurements made at a single point by means of the gage (see p. 25) from those based on full profiles of water surface and bed of débris. The former were used exclusively in the drawing of the representative lines, but not because they were regarded as of higher authority. It was thought best not to combine data which in certain cases were known to be incongruous; and the gage observations covered the whole range of the work, while the profiles did not. The measurements by profile were used in criticising the measurements by gage, and they determined the acceptance or rejection of certain gage measurements. It was noted that in some series of observations the depth measurements by the two methods were in close accord, while in others there was a large systematic difference; and certain series were rejected because of such large differences.

The plots were made to distinguish also the observations associated with different modes of traction—the dune, smooth, and antidune modes. The observations with the smooth mode were assumed to be best, as a class; and these, together with the observations connected with the transitional phases of traction, were used to fix an initial point of each representative line. The direction of the line was then adjusted by eye estimate to make it representative of all the points of the particular series. In this adjustment consideration was given to the conditions affecting the measurements of both depths and slopes.

The lines were first drawn for those observational series which appeared from the plots to be most harmonious, and for these there was discovered a tendency toward parallelism, within each group, of lines associated with a particular sand grade and channel width but differing as to discharge. For numerous other groups, involving very irregular observational positions, such parallelism was assumed; and under that assumption the better series of a group were made to control the directions of the lines for the poorer. For three groups the directions were interpolated by use of the directions found in affiliated groups.

For each observational series the direction of the representative line gave the value of n_1 in equations (21) and (22), and the intersection of the line with the axis of log d gave the value of b'.

TABLE 13.—*Values of n_1 in $d=\frac{b'}{S^{n_1}}$.*

Grade of débris.	Value of n_1 for trough having width (in feet) of—					
	0.23	0.44	0.66	1.00	1.32	1.96
(A)	....	0.44	....	....	0.50	0.60
(B)	0.49	[.44]	0.40	0.34	.70	.55
(C)	....	.44	.56	.53	.48–.58	.48
(D)	....	....	.40	....	.40–.59	....
(E)	....	....	[.35]	.34	....	....
(F)	....	....	.30	.26	[.26]	....
(G)	....	....	.28	.30	.26	....
(H)	....	....	.34	....	....	....

In Table 13 the determinations of n_1 are assembled, being arranged vertically with respect to grade of débris and horizontally with respect to width of trough. Collectively they indicate that, for constant discharge, the depth varies inversely with the slope and less rapidly than the slope. Comparatively they indicate considerable range in the rate of variation. There is some suggestion of system in the distribution of values of n_1, and it is especially probable that to the coarser débris belong the smaller values, but irregularity is, on the whole, more in evidence than system. The irregularity is to be ascribed largely to the imperfection of the data, and imperfection is believed to inhere especially in the measurements of depths by means of the gage. (See p. 25.)

Table 14 contains series of adjusted or interpolated values of depth. These were computed for slopes with the constant interval of 0.2 per cent, the range of slope within each series being approximately the same as the range through which the depth observations were made. The range is usually less than the range of slopes for which capacities were computed, the difference being occasioned by the fact that satisfactory measurements of depth could not be made during vigorous antidune traction. The computations were graphic, the values of adjusted depth being read directly from the logarithmic plot.

The number of series represented in the table is 73, being one-fourth less than the number for which capacities and slopes were tabulated. For 18 series the depth measurements were not reduced, the chief reasons for rejections being either (1) that the number of observations was very small, (2) that the observations included none made in connection with the smooth phase of traction, and (3) that the measurements with gage differed systematically by a large amount from corresponding measurements by the method of profiles.

TABLE 14.—*Adjusted values of depth of current (d), with values of mean velocity (V_m) and form ratio $\left(R=\frac{d}{w}\right)$.*

[n_1, Exponent in adjusting formula (21); p. e., probable error, in per cent, of adjusted values.]

Grade..	(A)			(A)			(A)			(A)			(A)		
w......	1.32			1.32			1.96			1.96			1.96		
Q......	.363			.734			.363			.734			1.119		
n_1......	.50			.50			.60			.60			.60		
p. e....	1.5			1.8			0.7			1.7			3.4		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2	0.218	1.25	0.165	....	....	....	....	....	....	0.255	1.47	0.130	0.232	3.35	0.118
.4	.154	1.78	.117	0.227	2.45	0.172	0.136	1.36	0.170	.167	2.24	.085	.182	4.25	.093
.6	.126	2.09	.096	.185	3.00	.141	.107	1.74	.155	.131	2.88	.067	.153	5.05	.078
.8	.109	2.53	.083	.160	3.45	.122	.090	2.05	.046	.110	3.41	.056	....	....	....
1.0	.098	2.83	.074	....	....	....	.079	2.35	.040	....	....	....	....	....	....
1.2	.090	3.10	.068	....	....	....	.071	2.62	.036	....	....	....	....	....	....
1.4	....	....	....	....	....	....	.064	2.87	.033	....	....	....	....	....	....

TABLE 14.—*Adjusted values of depth of current* (d), *with values of mean velocity* (V_m) *and form ratio* $\left(R=\frac{d}{w}\right)$—Con.

Grade	(B)			(B)			(B)			(B)			(B)		
w	.23			.23			.44			.44			.66		
Q	.093			.182			.093			.182			.093		
n_1	.49			.49			[.44]			[.44]			.55		
p. e.	3.3						5.5			2.6			2.3		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.4															
.6							0.128	1.73	0.294	0.220	1.90	0.502			
.8	0.200	2.02	0.880	0.327	2.43	1.43	.113	1.96	.259	.184	2.27	.421			
1.0	.179	2.17	.780	.292	2.70	1.28	.102	2.08	.235	.163	2.56	.371	0.079	1.80	0.118
1.2	.163	2.49	.715	.266	2.96	1.17	.094	2.36	.216	.146	2.81	.336	.069	2.03	.105
1.4	.150	2.68	.660	.247	3.02	1.08	.088	2.53	.202	.135	3.04	.310	.063	2.25	.095
1.6	.141	2.86	.620	.231	3.42	1.01	.083	2.67	.190				.057	2.45	.087
1.8	.133	3.04	.583	.218	3.61	.96	.079	2.82	.182				.053	2.65	.081
2.0							.075	2.95	.173				.050	2.82	.076
2.2							.072	3.08	.167				.047	3.00	.072
2.4							.069	3.20	.160				.045	3.15	.068
2.6							.067	3.32	.154						

Grade	(B)			(B)			(B)			(B)			(B)		
w	.66			.66			.66			1.00			1.00		
Q	.182			.363			.545			.182			.363		
n_1	.40			.40			.40			.34			.34		
p. e.	2.1			2.1			2.0			3.3			2.5		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2	0.208	1.33	0.317				0.427	1.97	0.650				0.239	1.53	0.239
.4	.176	1.76	.240	0.246	2.22	0.373	.323	2.60	.490				.188	1.94	.188
.6	.133	2.08	.203	.210	2.63	.318	.274	3.04	.418	0.101	1.81	0.101	.164	2.24	.164
.8	.118	2.34	.181	.187	2.95	.283	.245	3.40	.370	.091	2.00	.091	.148	2.46	.148
1.0	.108	2.56	.165	.171	3.23	.259	.223	3.70	.340	.084	2.15	.084	.137	2.66	.137
1.2	.100	2.75	.153	.158	3.49	.240	.207	3.97	.315	.079	2.39	.079	.128	2.83	.128
1.4	.095	2.94	.144	.148	3.71	.226	.194	4.24	.296	.075	2.40	.075	.122	2.98	.122
1.6	.090	3.10	.137							.072	2.51	.072	.117	3.12	.117
1.8	.085	3.25	.130							.069	2.62	.069	.112	3.25	.112
2.0	.082	3.38	.125							.066	2.71	.066	.108	3.36	.108
2.2	.079	3.50	.120							.064	2.80	.064	.105	3.48	.105
2.4										.062	2.92	.062			
2.6										.061	3.00	.061			

Grade	(B)			(B)			(B)			(B)			(B)		
w	1.00			1.32			1.32			1.32			1.96		
Q	.734			.182			.545			.734			.363		
n_1	.34			.70			.70			.70			.55		
p. e.	1.4			2.5			2.4			2.6			3.3		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2	0.347	2.10	0.347	0.200	0.68	0.153									
.4	.275	2.68	.275	.124	1.12	.094	0.233	1.76	0.176	0.256	2.10	0.194	0.117	1.58	0.059
.6	.239	3.10	.239	.094	1.48	.071	.175	2.35	.133	.193	2.83	.146	.094	1.98	.047
.8	.217	3.41	.217	.077	1.82	.057	.143	2.88	.108	.158	3.48	.120	.080	2.33	.041
1.0	.200	3.67	.200	.066	2.13	.050	.123	3.38	.093				.071	2.65	.036
1.2				.058	2.42	.046	.108	3.82	.082				.064	2.93	.033
1.4				.052	2.70	.039	.097	4.27	.073				.059	3.20	.030
1.6				.047	2.96	.036							.054	3.43	.028
1.8				.043	3.20	.033							.051	3.67	.026
2.0				.040	3.45	.031							.048	3.88	.025
2.2				.038	3.70	.029									
2.4				.036	3.92	.027									

Grade	(B)			(B)			(B)			(C)			(C)		
w	1.96			1.96			1.96			.44			.44		
Q	.545			.734			1.119			.093			.182		
n_1	.55			.55			.55			.44			.44		
p. e.	2.8			5.4			3.8			0.6			0.7		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2				0.268	1.40	0.136	0.400	1.45	0.203						
.4	0.168	1.63	0.086	.183	2.05	.094	.271	2.13	.138						
.6	.135	2.04	.069	.147	2.55	.075	.217	2.66	.110	0.163	1.28	0.370	0.240	1.73	0.546
.8	.115	2.38	.059	.126	2.98	.064	.185	3.11	.094	.143	1.46	.328	.213	1.96	.480
1.0	.102	2.70	.052	.112	3.35	.057	.163	3.51	.083	.130	1.62	.298	.192	2.16	.436
1.2	.092	2.30	.047				.147	3.89	.075	.120	1.75	.275	.177	2.34	.400
1.4	.085	2.26	.043							.112	1.87	.256	.165	2.50	.375
1.6										.106	2.00	.242	.157	2.66	.355
1.8										.101	2.10	.230			

TABLE 14.—*Adjusted values of depth of current (d), with values of mean velocity (V_m) and form ratio* $\left(R=\frac{d}{w}\right)$—Con.

Grade	(C)			(C)			(C)			(C)			(C)		
w	.66			.66			.66			.66			.66		
Q	.093			.182			.363			.545			.734		
n_1	.56			.56			.56			.56			.56		
p. e.	0.8			1.8			1.4			1.3			1.9		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2				0.270	1.03	0.410				0.562	1.43	0.850			
.4	0.132	1.08	0.199	.183	1.52	.277	0.288	1.88	0.438	.381	2.13	.580			
.6	.105	1.35	.160	.146	1.89	.222	.230	2.38	.350	.304	2.68	.461	0.340	3.26	0.515
.8	.090	1.58	.135	.125	2.21	.188	.196	2.80	.298	.260	3.16	.392	.290	3.82	.440
1.0	.079	1.79	.119	.110	2.50	.167	.173	3.20	.264	.228	3.60	.346	.255	4.34	.386
1.2	.071	1.97	.107	.100	2.77	.150	.157	3.53	.238	.206	4.00	.312	.230	4.80	.349
1.4	.065	2.14	.099	.092	3.00	.138									
1.6	.061	2.30	.092	.085	3.23	.128									
1.8	.057	2.45	.086	.080	3.44	.120									
2.0	.054	2.60	.082	.075	3.64	.113									
2.2	.051	2.72	.077	.071	3.83	.107									
2.4	.048	2.86	.074												
2.6	.046	3.00	.071												

Grade	(C)			(C)			(C)			(C)			(C)		
w	1.00			1.00			1.00			1.00			1.32		
Q	.182			.363			.545			.734			.182		
n_1	.53			.53			.53			.53			.58		
p. e.	1.9			0.9			1.5			2.2			1.7		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2				0.307	1.18	0.307				0.450	1.66	0.450			
.4	0.139	1.30	0.139	.212	1.72	.212				.310	2.39	.310			
.6	.113	1.62	.113	.171	2.14	.171				.250	2.96	.250	0.100	1.38	0.075
.8	.098	1.88	.098	.147	2.49	.147	0.190	2.86	0.190	.214	3.45	.214	.084	1.65	.064
1.0	.086	2.13	.086	.130	2.80	.130	.170	3.22	.170	.190	3.88	.190	.074	1.88	.056
1.2	.078	2.34	.078	.118	3.08	.118	.153	3.54	.153	.172	4.26	.172	.067	2.09	.050
1.4	.072	2.55	.072	.108	3.34	.108	.141	3.84	.141				.061	2.29	.046
1.6	.067	2.74	.067	.102	3.60	.102	.132	4.14	.132				.056	2.47	.043
1.8	.063	2.90	.063				.123	4.52	.123				.053	2.73	.040
2.0	.059	3.08	.059										.050	2.81	.037
2.2	.056	3.24	.056										.047	2.96	.035
2.4	.054	3.38	.054										.045	3.12	.034
2.6													.043	3.27	.032

Grade	(C)			(C)			(C)			(C)			(C)		
w	1.32			1.32			1.32			1.96			1.96		
Q	.363			.545			.734			.363			.545		
n_1	.48			.48			.48			.48			.48		
p. e.	2.3			.8			1.1			1.2			1.1		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2							0.344	1.63	0.261						
.4	0.168	1.66	0.128				.246	2.27	.187	0.132	1.18	0.068	0.166	1.66	0.085
.6	.138	2.00	.105	0.174	2.36	0.132	.203	2.76	.153	.108	1.44	.056	.136	2.02	.069
.8	.120	2.28	.092	.152	2.71	.115	.177	3.17	.134	.095	1.66	.048	.118	2.34	.060
1.0	.108	2.54	.082	.136	3.02	.104	.158	3.50	.120	.085	1.85	.043	.106	2.61	.054
1.2	.099	2.76	.075	.125	3.30	.095	.145	3.84	.110	.078	2.02	.040	.097	2.86	.049
1.4	.092	2.96	.070	.116	3.54	.088	.135	4.14	.102	.072	2.18	.037	.090	3.10	.046
1.6	.086	3.15	.065	.108	3.78	.083	.124	4.40	.096	.068	2.32	.035	.084	3.30	.043
1.8										.064	2.46	.033	.079	3.50	.040
2.0										.061	2.59	.031	.075	3.69	.038
2.2										.058	2.71	.030			

Grade	(C)			(C)			(D)			(D)			(D)		
w	1.96			1.96			0.66			0.66			0.66		
Q	.734			1.119			.093			.182			.545		
n_1	.48			.48			.40			.40			.40		
p. e.	1.0			1.0			1.3			1.1			1.5		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2													0.461	1.81	0.640
.4	0.194	1.96	0.099	0.240	2.40	0.122				0.172	1.61	0.258	.349	2.38	.531
.6	.159	2.38	.081	.197	2.92	.100				.143	1.92	.217	.296	2.80	.450
.8	.138	2.73	.070	.172	3.36	.088	0.087	1.63	0.132	.127	2.17	.192	.265	3.14	.403
1.0	.124	3.04	.063	.153	3.73	.078	.080	1.78	.132	.115	2.40	.174	.242	3.42	.369
1.2	.113	3.31	.058	.140	4.08	.072	.074	1.91	.112	.107	2.59	.161	.224	3.69	.342
1.4	.105	3.56	.053				.069	2.02	.105	.100	2.77	.151	.212	3.91	.322
1.6	.099	3.80	.050				.066	2.13	.100	.094	2.92	.143	.200	4.13	.305
1.8							.063	2.23	.095	.090	3.07	.135	.191	4.33	.291
2.0							.060	2.33	.091	.086	3.21	.130	.183	4.50	.280
2.2							.058	2.42	.088	.082	3.36	.125			
2.4							.056	2.50	.085	.079	3.48	.120			
2.6							.054	2.58	.082	.077	3.60	.116			

TABLE 14.—*Adjusted values of depth of current* (d), *with values of mean velocity* (V_m) *and form ratio* $\left(R=\frac{d}{w}\right)$—Con.

Grade	(D)			(D)			(D)			(D)			(D)		
w	1.00			1.00			1.00			1.00			1.32		
Q	.182			.363			.545			.734			.363		
n_1	.42			.42			.42			.42			.40		
p. e.	.8			1.8			.9			1.5			2.1		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2				0.278	1.32	0.278									
.4				.207	1.77	.207	0.252	2.16	0.252				0.163	1.68	0.133
.6	0.116	1.57	0.116	.174	2.10	.174	.213	2.56	.213	0.260	2.87	0.260	.138	1.98	.106
.8	.103	1.76	.103	.154	2.36	.154	.188	2.89	.188	.231	3.21	.231	.124	2.22	.094
1.0	.094	1.93	.094	.140	2.60	.140	.172	3.19	.172	.210	3.51	.210	.113	2.43	.086
1.2	.087	2.09	.087	.130	2.81	.130	.158	3.43	.158	.195	3.80	.195	.105	2.62	.080
1.4	.081	2.22	.081	.122	3.00	.122	.149	3.67	.149	.183	4.04	.183	.099	2.78	.075
1.6	.077	2.34	.077	.115	3.18	.115	.141	3.88	.141	.173	4.28	.173	.094	2.93	.071
1.8	.073	2.47	.073	.108	3.33	.108	.134	4.08	.134	.164	4.49	.164	.090	3.07	.068
2.0	.070	2.57	.070	.104	3.48	.104	.128	4.27	.128	.157	4.69	.157	.086	3.20	.065
2.2	.067	2.67	.067	.101	3.63	.101	.123	4.44	.123						
2.4	.065	2.77	.065	.097	3.77	.097									
2.6	.063	2.87	.063												
2.8	.061	2.95	.061												
3.0	.059	3.04	.059												

Grade	(D)			(E)			(E)			(E)			(E)		
w	1.32			.66			.66			1.00			1.00		
Q	.734			.363			.734			.182			.363		
n_1	.59			[.35]			[.35]			.34			.34		
p. e.	1.7			1.6						2.6			1.6		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2	0.423	1.30	0.323										0.252	1.44	0.252
.4	.281	1.97	.214										.198	1.83	.198
.6	.222	2.50	.169										.173	2.10	.173
.8	.187	2.97	.143										.157	2.32	.157
1.0	.164	3.38	.125	0.129	2.14	0.195	0.206	2.66	0.313	0.097	1.88	0.097	.146	2.50	.146
1.2	.147	3.78	.112	.122	2.28	.183	.194	2.83	.293	.091	2.02	.091	.137	2.66	.137
1.4				.115	2.40	.173	.183	3.00	.285	.087	2.13	.087	.129	2.80	.129
1.6				.109	2.52	.166	.175	3.14	.265	.083	2.22	.083	.123	2.94	.123
1.8										.080	2.31	.080	.118	3.05	.118
2.0										.077	2.39	.077	.114	3.16	.114
2.2													.112	3.27	.112
2.4													.108	3.37	.108

Grade	(E)			(F)			(F)			(F)			(F)		
w	1.00			.66			.66			1.00			1.00		
Q	.734			.182			.363			.182			.363		
n_1	.34			.30			.30			.26			.26		
p. e.	2.6			1.5			0.2						1.2		
S	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R	d	V_m	R
0.2	0.395	1.85	0.395												
.4	.312	2.34	.312												
.6	.272	2.70	.272												
.8	.246	2.98	.246				0.227	2.43	0.345				0.162	2.24	0.162
1.0	.228	3.23	.228	0.134	2.05	0.205	.213	2.59	.321	0.099	1.83	0.099	.153	2.38	.153
1.2	.214	3.44	.214	.127	2.16	.194	.201	2.74	.303	.095	1.92	.095	.145	2.50	.145
1.4	.203	3.63	.203	.122	2.28	.185	.192	2.86	.290	.091	2.00	.091	.139	2.60	.139
1.6	.194	3.80	.194	.117	2.36	.178	.185	2.98	.280	.088	2.07	.088	.135	2.69	.135
1.8				.113	2.46	.172	.178	3.08	.270	.085	2.14	.085	.131	2.78	.131
2.0				.108	2.52	.167	.173	3.18	.262	.083	2.20	.083	.127	2.85	.127
2.2				.106	2.60	.162	.167	3.28	.254	.081	2.26	.081			
2.4				.103	2.67	.157				.079	2.32	.079			
2.6				.101	2.74	.153				.078	2.37	.078			

TABLE 14.—*Adjusted values of depth of current (d), with values of mean velocity (V_m), and form ratio* $\left(R=\frac{d}{w}\right)$—Con.

Grade	(F)			(G)			(G)			(G)			(G)		
w	1.32			.66			.66			.66			1.00		
Q	.363			.363			.734			1.119			.363		
n_1	[.26]			[.26]			[.26]			[.26]			.30		
p. e.	2.1			0.2			0.2			0.4			0.4		
S	*d*	V_m	*R*	*d*	V_m	*R*	*d*	V_m	*R*	*d*	V_m	*R*	*d*	V_m	*R*
0.6							0.389	2.86	0.588	0.465	3.68	0.705			
.8				0.222	2.49	0.336	.358	3.10	.540	.436	3.92	.660			
1.0	0.127	2.17	0.096	.218	2.65	.315	.338	3.30	.508	.413	4.12	.626	0.158	2.30	0.158
1.2	.121	2.27	.092	.198	2.80	.300	.320	3.48	.481	.396	4.30	.600	.149	2.42	.149
1.4	.116	2.36	.088	.189	2.91	.287	.306	3.63	.460	.382	4.44	.580	.143	2.54	.143
1.6	.112	2.44	.085	.183	3.02	.277	.294	3.78	.443	.371	4.58	.561	.137	2.65	.137
1.8	.108	2.52	.083	.176	3.13	.268	.285	3.90	.430	.361	4.70	.548	.132	2.74	.132
2.0	.106	2.59	.081	.172	3.23	.260	.276	4.02	.418	.352	4.80	.532	.128	2.83	.128
2.2	.103	2.65	.079	.167	3.30	.253	.270	4.13	.405	.346	4.90	.522	.124	2.93	.124
2.4				.163	3.39	.247	.263	4.22	.395	.338	5.00	.512	.121	3.00	.121
2.6				.158	3.46	.242	.257	4.32	.387	.332	5.10	.502	.118	3.07	.118
2.8							.252	4.41	.378	.327	5.19	.494	.116	3.14	.116
3.0													.113	3.22	.113

Grade	(G)			(G)			(G)			(G)		
w	1.00			1.00			1.32			1.32		
Q	.734			1.119			.363			.734		
n_1	.30			.30			.26			.26		
p. e.	0.6			0.5			1.1			1.2		
S	*d*	V_m	*R*	*d*	V_m	*R*	*d*	V_m	*R*	*d*	V_m	*R*
0.6	0.287	2.57	0.287	0.376	3.00	0.376						
.8	.363	2.80	.263	.344	3.27	.344				0.216	2.60	0.164
1.0	.246	2.99	.246	.322	3.50	.322				.203	2.75	.154
1.2	.232	3.16	.232	.302	3.70	.302				.194	2.89	.147
1.4	.222	3.30	.222	.290	3.86	.290				.186	3.00	.141
1.6	.213	3.43	.213	.279	4.04	.279	0.114	2.41	0.087	.180	3.12	.136
1.8	.206	3.56	.206	.269	4.18	.269	.112	2.48	.084	.174	3.22	.132
2.0	.199	3.68	.199	.260	4.31	.260	.108	2.55	.082	.169	3.30	.128
2.2	.194	3.78	.194	.253	4.43	.253	.105	2.62	.080	.165	3.39	.125
2.4	.188	3.87	.188	.247	4.55	.247	.103	2.67	.078	.162	3.47	.122
2.6	.184	3.96	.184	.241	4.61	.241	.101	2.74	.077	.158	3.54	.120
2.8	.180	4.05	.180				.099	2.78	.075		3.61	.118
3.0							.098	2.83	.074			
3.2							.096	2.87	.073			

Grade	(G)			(H)			(H)			(H)		
w	1.32			.66			.66			.66		
Q	1.119			.363			.734			1.119		
n_1	.26			.34			.34			.34		
p. e.	0.7			1.7			0.9			0.5		
S	*d*	V_m	*R*	*d*	V_m	*R*	*d*	V_m	*R*	*d*	V_m	*R*
0.6	0.303	2.80	0.230							0.560	2.83	0.850
.8	.281	3.03	.213				0.382	2.93	0.580	.507	3.12	.770
1.0	.264	3.22	.200	0.220	2.52	0.336	.354	3.16	.538	.470	3.36	.713
1.2	.251	3.38	.190	.207	2.68	.316	.333	3.36	.504	.441	3.59	.670
1.4	.241	3.52	.183	.197	2.82	.300	.316	3.53	.479	.420	3.78	.636
1.6	.232	3.66	.176	.188	2.96	.286	.302	3.70	.458	.400	3.94	.608
1.8	.226	3.78	.170	.181	3.07	.276	.290	3.84	.440	.385	4.10	.584
2.0	.219	3.88	.165	.174	3.18	.267	.280	4.00	.425	.372	4.25	.564
2.2	.214	3.98	.162	.168	3.29	.258	.271	4.13	.411	.360	4.40	.548
2.4	.208	4.07	.157	.164	3.39	.250	.263	4.25	.399	.349	4.50	.530
2.6	.203	4.17	.154	.159	3.48	.243	.256	4.36	.388	.341	4.64	.518
2.8							.250	4.46	.379			
3.0							.244	4.57	.370			

PRECISION.

Probable errors were computed in the manner described on page 73. The largest error found for a series of adjusted values of depth is ±5.5 per cent; and the arithmetical mean of the 66 determinations is ±1.70 per cent. The mean of 66 determinations of the probable error of an observation of depth is ±5.47 per cent; and the arithmetical mean of the (710) residuals, or differences (irrespective of sign) between observed and adjusted depths, is 6.65 per cent.

The residuals of any series, computed as fractional parts of the quantity measured, are greater for small depths than for large. Computed in fractions of a foot, they do not vary notably with depth.

The average value of the depths to which these measures of precision pertain is 0.176 foot. Using this factor to convert the preceding average percentage errors into (approximately) equivalent linear errors, we have, for the average of probable errors of adjusted depths ±0.003 foot; for the average of probable errors of observed depths ±0.010 foot, and for the average residual 0.011 foot.

The errors thus estimated include (1) the strictly accidental errors of observation, (2) the more or less systematic influences exerted on the measurements by the diverse modes of traction, and (3) errors occasioned by the assumptions underlying the method of reduction; but they do not include such systematic errors as are shown by comparing gage measurements with profile measurements. (See p. 26.) In connection with the descriptions of methods of measurement it is stated that the probable error of a single measurement by gage was computed from the comparison of values by two methods (in all cases where both are used), and on the assumption that the measures by the profile method are relatively accurate. This computation gave a value smaller than ±0.010 foot, namely, ±0.007 foot. The groups of measurements to which the two estimates of precision apply are not the same, although they overlap. One group includes all gage measurements of 66 series, their number being 710; the other group includes all those gage measurements of the 92 series which were checked by profile measurements, their number being 118.

By comparing these results with those reported on page 74, it is seen that the computed probable errors for depth are smaller than those for capacity. It is nevertheless believed that the measurements of load were more precise than those of depth. The discrepancy is accounted for by considering, first, that the estimates of precision, instead of applying simply to the measurements of load and depth, apply to capacity for load as a function of slope and to depth as a function of slope; and, second, that the relation of load to slope is subject to continual rhythmic variation, while the relation of depth to slope is little influenced by that variation.

MEAN VELOCITY.

As the discharge, Q, equals the product of the sectional area of the current, wd, by the mean velocity, V_m, we have

$$V_m=\frac{Q}{wd} \tag{23}$$

For each observational series, Q and w are constant and

$$V_m \propto \frac{1}{d} \tag{24}$$

Substituting for d its value in the interpolation equation (21), and remembering that b' is a constant for each series, we obtain

$$V_m \propto S^{n_1} \tag{25}$$

By means of (23) a value of mean velocity was computed for each adjusted value of d, and these values are given in Table 14. They involve all the assumptions of the formula for the reduction of the depth observations and have the same fractional measures of precision.

FORM RATIO.

The adjusted values of d were used also for the computation of the form ratio, R, which is the quotient of the depth of the current by its width; and a value of R is tabulated with each value of d. Within each observational series the form ratios are proportional to the depths, and they have the same measures of precision.

GRAPHIC COMPUTATION.

All these computations were made by graphic methods. For each observational series a plot was made on logarithmic section paper. By way of illustration the plot for grade (B), width 1.96 feet and discharge 1.119 ft.^{3}/sec. is reproduced in figure 28, the finer lines of the logarithmic net being omitted. The vertical lines represent values of slope; the horizontal lines, capacity, depth, mean velocity, and form ratio. For the convenience of having the graphs close together their scales are made to differ, the ratio of one to another being 10, 100, or 1,000. In the particular instance shown in figure 28 the same line represents $C=100$, $d=0.1$, $V_m=1.0$, and $R=0.1$. With use of this notation were plotted the equations for C, d, V_m, and R, as functions of S. In their logarithmic forms these are

$$\log d=\log b'-n_1 \log S$$

$$\log V_m=\log \frac{Q}{w}-\log\ d=\log \frac{Q}{w}-\log b'+n_1 \log S$$

$$\log R=\log d-\log w=\log \frac{b'}{w}-n_1 \log S$$

$$\log C=\log b_1+n \log (S-\sigma)$$

Their loci are the straight lines marked d, V_m, and R and the curve marked C.

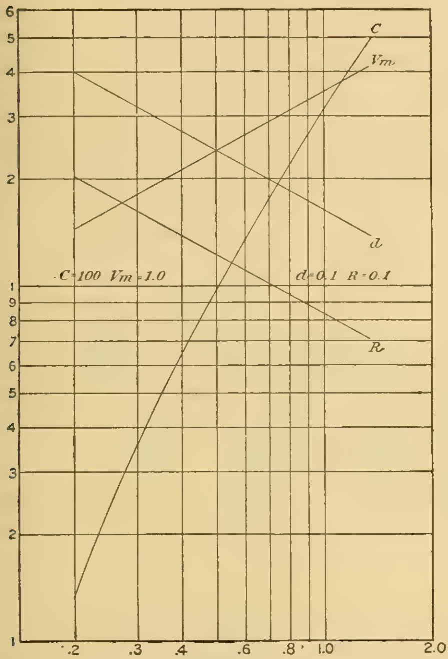

FIGURE 28.—Logarithmic computation sheet, combining relations of capacity, mean velocity, form ratio, and slope.

After the preparation of these constructions the values of d, V_m, and R, corresponding to the selected series of values of S, were read from the sheets, affording the data of Table 14. The sheets had also many other uses, for in recording the relations of four interdependent variables to slope they also recorded their relations to one another. The points of the four loci which lie in the same vertical represent corresponding values of the several variables, and this property made it possible to read from the plot the value of a variable corresponding to a particular value of one of the others. For example, if it is desired to learn the capacity corresponding to a mean velocity of 2 ft./sec., the intersection of the velocity line with the line representing 2 on the scale of velocities is first found. From that intersection a vertical is followed or drawn to the capacity line and the position of the second intersection is read on the capacity scale.

A large part of the numerical data cited in the following discussions were either taken directly from the computation sheets or based upon them.

The accuracy of the computations by logarithmic graph may be characterized by saying that it is slightly below that by slide rule. The theoretic accuracy is the same, but tests of the logarithmic paper employed showed it to be a less perfect instrument than the slide rule, which was used for a large body of routine computations.

CHAPTER III.—RELATION OF CAPACITY TO SLOPE.

INTRODUCTION.

A series of chapters, beginning with this one, are given to the discussion of the observational data. The discussions make use of the adjusted values of capacity for stream traction, slope of stream bed, and depth of current, with their derivatives, contained in Tables 12 and 14. Associated with those adjusted values are certain grades of transported material, or degrees of fineness, certain widths of channel, and certain discharges of the transporting stream. The leading subjects of discussion are the relations of capacity to slope, discharge, fineness, and form ratio, but consideration is also given to the relations of capacity to depth and velocity, and to the relations which duty, efficiency, and depth bear to various conditions. The discussion is essentially empiric, its course being guided in small degree only by theoretic considerations.

The treatment of the relation of capacity to slope first views it as conditioned by channels of fixed width, and then as subject to the relatively ideal condition of fixed form ratio.

IN CHANNELS OF FIXED WIDTH.

THE CONDITIONS.

In each observational series the width of channel was constant, and so also were the discharge and the grade of débris constituting the load. As the load was changed, the slope responded; velocity responded to change of slope; and with variation of velocity went variation of depth. The ratio of depth to width, or the form ratio, was therefore a variable; so that the stream which dragged a large load down a steep slope differed in form, and to that extent in type, from the stream which moved a small load along a gentle slope. In a few cases it is possible so to combine data from different series as to discover the relation of capacity to slope for streams which have similar cross sections; and these will be examined in another place; but the principal discussion relates to streams with constant width and variable form ratio.

THE SIGMA FORMULA.[1]

Those properties of the formula

$$C=b_1(S-\sigma)^n \text{ ----------- } (10)$$

which determined its adoption for the reduction of the observational data to a more orderly system led also to the consideration of its availability as an empiric formula for the general relation of the stream's capacity for traction to the slope of its bed. With a view to this second use, the specific values of b_1, σ, and n derived for the purpose of the reduction—values which are recorded in Table 15—were arranged and combined in various ways, in order to discover, if possible, definite relations to the several conditions in accordance with which the experiments were varied. It has already been noted (p. 71) that the critical slope, σ, varies inversely with fineness of débris, with discharge, and (probably) with range of fineness within a grade, and that it varies inversely with width of trough when that width is relatively small, but directly with width when width is relatively large.

$$\sigma=f\,(\grave{F}, \grave{H}, \breve{w}, \grave{Q}) \text{ --------- } (26)$$

written to express these relations in symbols, introduces H to designate range of fineness and distinguishes trend of function by means of accents. As the notation by accents will be frequently used, its definition may be made explicit. Where the function is direct, or *increasing*, its value increasing with the increase of the independent variable, the symbol of the variable is given the acute accent (ʹ). Where the function is inverse, or *decreasing*, its value decreasing with increase of the variable, the grave accent (`) is used. For a *maximum* function, first increasing and then decreasing (ˆ) is used, and for a *minimum* function (˘).

The discussion of the values of b_1 showed (1) that they vary directly and in marked degree, but irregularly, with F_2, (2) that they vary directly and approximately in simple ratio, with Q, and (3) that they vary increasingly, if at all, but very slightly with w, while (4) a relation to H could not be disentangled from the relation to F_2. The discussion of the values of n showed (1) that they vary inversely and irregularly with F_2, (2) that they vary inversely and more regularly with Q, and (3) that the variation in respect to w is direct for small widths and inverse for large widths, while (4) the relation to H is not separable.

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[1] Since these lines were penned I have discovered that this title duplicates one in the field of higher mathematics. Nevertheless I retain it because of its mnemonic convenience. The two fields of application are so distinct that serious confusion will not be occasioned.

The data on the three parameters are summarized in equation (27), which is an expansion of equation (10). In all probability f_I and f_{II} are as complex as f, but no factors are introduced of which the influence was not definitely shown by the discussion.

$$C=f_{I}\,(\acute{F}_2,\acute{Q})\,[S-f\,(\grave{F}_2,\grave{H},\breve{w},\grave{Q})]^{f_{II}^{(\grave{F},\hat{w},\grave{Q})}} \quad \text{--}(27)$$

This equation is subject to a qualification connected with the assignment of values to σ. It will be recalled that that assignment was somewhat arbitrary, and also that the values of σ entered into the computation of the values of b_1 and n. A systematic error in the values of σ would therefore cause systematic errors in the other parameters and might vitiate conclusions as to the laws of their variation. A search was made for evidence of such errors, the search making use of the principle (easily demonstrated) that a positive error in σ would cause a positive error in b_1 and a negative error in n. While the result of the search was negative, it is not to be supposed that the values of σ have high precision. To their errors, in combination with the obscure influences of the varying range of fineness and with the errors of observation, are to be ascribed the irregularities of the constants of the adjusting equations.

While the algebraic relations are such that minor errors in the values of σ might have important influence on values of b_1 and n, their influence on the interpolated values of C would be small.

The uncertainties affecting the several elements of equation (27) are so great that no attempt will be made to develop from it a definite and quantitative expression for the relation of capacity to slope. For this reason the preceding paragraphs have attempted to present only the general tenor of the discussion and have purposely omitted details. The results, despite important qualifications, show clearly that any general expression of the law connecting capacity and slope which might be based on formula (10) would be highly complex.

With reference to the main subject of this chapter, the following section is of the nature of a digression, its purpose being to define a method and terminology used in several of the succeeding chapters.

THE POWER FUNCTION AND THE INDEX OF RELATIVE VARIATION.

One of the algebraic forms to which the title *power function* is applied is

$$y=ax^n \quad \text{-----------}(28)$$

If the coefficient be suppressed, leaving

$$y \propto x^n$$

this is the exact equivalent of the familar "y varies as the nth power of x." This mode of comparing the rate of variation of one thing with the rate of variation of another is extensively employed, and it so commends itself by its simplicity that its use is constantly extended into fields where its applicability is approximate only. Having occasion to make much use of certain variants of this function, I find it important to obtain a clear conception of its properties and shall therefore give the matter somewhat elementary attention—with due apology to the mathematical reader.

If we consider x and y merely as numbers, the rate of variation with y with respect to x is the ratio of the differential increment of y to that of x. That ratio is

$$\frac{dy}{dx}=anx^{n-1} \quad \text{------------}(29)$$

If we consider x and y (and also the constant a) as powers of a common base, equation (28) becomes

$$\log y=\log a+n \log x \quad \text{-------}(30)$$

The rate of variation of log y with respect to log x is, differentiating,

$$\frac{d \log y}{d \log x}=n \quad \text{------------}(31)$$

Now, in saying that one quantity varies as a certain power of another, or in using such a function as (28), the index of variation, or that by which is indicated the comparative rate of variation, is the exponent n; and the value of this exponent, in terms of the variables, is found not in (29) but in (31). The expression "y varies as the nth power of x" is equivalent to "the rate of variation of y, considered as a power, is n times the rate of variation of x, considered as a power."

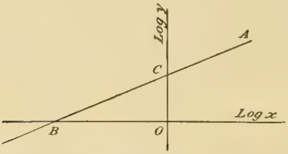

Figure 29.—Logarithmic locus of the power function.

An equivalent result would be attained if attention were given to the quality of the growth of x and y. Considering their growth as occurring by additive increments, equation (29) gives the ratio between their rates of increase. Considering their growth as a matter of multiplication by ratios, the additive increments are increments to logarithms, and equation (31) gives the ratio between rates of increase.

Equation (30), the logarithmic equivalent of (28), is the equation of a straight line. Representing it by AB in figure 29, its inclination $\frac{CO}{BO}$ equals n, and its intersection with the axis of log y gives $CO = \log a$. These familiar properties enhance the utility of function (28) by enabling the investigator to discuss its constants on logarithmic section paper.

In many, probably a large majority, of the physical problems to which the power function is applied, it is found that the exponent, n, does not have a constant value through the entire range of observed values of x and y. The locus of $\log y = f(\log x)$ is then not a straight line but a curve, which we may represent by AB in figure 30. At any point of the curve C, its minute element, not distinguishable from a straight line, has an inclination, $\frac{CE}{DE}$, which is homologous with n in (31) and (28) and which we may call n_2. The value of n_2 varies from point to point of the curve, so that if we try to express the relation of y to x in the form of equation (28) we must regard the exponent as a variable.

The element at C may also be thought of as part of the tangent line CD, of which the equation is

$$\log y = \overline{FO} + n_2 \log x$$

whence

$$y = \log^{-1} \overline{FO} x^{n_2}$$

On comparing this with (28), it is seen that $\log^{-1} \overline{FO}$ corresponds to a. Let us replace it by a_1, giving

$$y = a_1 x^{n_2} \text{..............} (32)$$

It is evident that for any other point of the curve, as C', the tangent intersects the axis of log y at a point different from F, and this corresponds to a different value of a_1. In other words, if we would express in an equation of the type of (28) the same relation between two variables that is expressed by the logarithmic locus in figure 30, we must make the coefficient as well as the exponent variable.

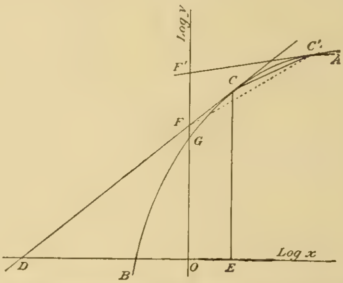

Figure 30.—Locus of log $y = f(\log x)$, illustrating the nature of the index of relative variation.

The values of a_1 and n_2 are evidently functions of the independent variable, x.

It is possible to give to the relation shown by the logarithmic locus an algebraic expression which is identical in form with (28) and in which the coefficient is a constant. That is to say, it is possible to segregate the variability of parameters in the exponent; but when that is done the exponent no longer corresponds to the expression "varies as the nth power of," and the expression thus lacks the essential quality of (28). To illustrate, let us assume that the position of the point F is fixed, so as to give a constant value to a_1. The values of n_2 then correspond to the incilnations of lines FC, FC'', etc., drawn to points on the curve; but these lines are not tangents and their inclinations are not those of the corresponding elements of the curve.

In order to satisfy the condition, from equation (28), that $y=a$ when $x=1$ and $\log x=0$, the fixed point must be at the intersection, G, of the curve with the axis of $\log y$. The lines connecting it with other points of the curve are therefore chords.

In the discussions of our laboratory data use will be made of both these variants of the power function; and they will be distinguished, from one another as well as from (28), by the following notation. In

$$y=vx^i \text{ - - - - - - - - - - - - - - } (33)$$

the coefficient and exponent are both variable and are functions of x. The symbol v is chosen for the coefficient to signalize its variability. The exponent, i, denotes the instantaneous ratio of the variation of y to the variation of x, when those variations are viewed as ratios. It is the first differential coefficient of $\log y$ with respect to $\log x$, and it will be spoken of as the *index of relative variation.*

In

$$y=cx^j \text{ - - - - - - - - - - - - - - } (34)$$

the coefficient is constant and the exponent variable.

Whenever, in the investigation of the natural law connecting two variables, pairs of simultaneous values of the variables are known by observation, it is possible to plot a curve representing empirically $\log y=f(\log x)$—such a curve as $ACGB$ in figure 30. The directions of the elements of that curve, or the values of i, are essentially facts of observation. They depend exclusively on the phenomena and are independent of the units in which observational data are expressed. It is different with the values of j, for those depend on the position of the point, G, in which the curve intersects the axis of $\log y$, and therefore on the position of the axis. The position of the axis corresponds to $\log x=0$ or $x=1$ and is thus dependent on the magnitude of the unit by which the independent variable is measured.

In other chapters of this report much attention is given to the values of i, and the discussion of the variations of such values is used as a mode of treating empirically the relations between the various factors of the general problem of traction.

THE SYNTHETIC INDEX.

Recurring to figure 30, let us give attention to a restricted portion of the curve, for example, the part between C and C'. The value of i corresponding to the point C is the inclination of the line CF; the value of i corresponding to C' is the inclination of $C'F'$. Between the two are a continuous series of other values. The inclination of the chord connecting C and C', conconsidered as a ratio or exponent, is intermediate between the extreme values of i. If the sequence of values follows a definite law, the value given by the chord equals some sort of a mean derived from the others; and, in any case, it is in a sense representative of the group. It may be called a *synthetic index* of relative variation between the indicated limits.

If the coordinates of C be $\log x'$ and $\log y'$, and the coordinates of C' be $\log x''$ and $\log y''$, then, representing the synthetic index by I,

$$I=\frac{\log y''-\log y'}{\log x''-\log x'} \text{ - - - - - - - - - } (35)$$

As the direction of the chord depends on the positions of C and C' upon the curve, so the value of I depends on the limits between which it is computed. As the direction of the chord gives no information concerning the direction of any part of the curve, so the value of I can not be used to determine any particular value of i. It is used in the following pages for the comparison of different functions for which the data span approximately the same range of conditions.

APPLICATION TO THE SIGMA FUNCTION.

Let us now represent the relation of capacity to slope by an equation of form (33),

$$C=v_1\,S^{i_1} \text{ - - - - - - - - - - - - - } (36)$$

and develop the value of i_1 from equation (10). The logarithmic equivalent of (10) (p. 64) is

$$\log C = \log b_1 + n \log (S - \sigma) \quad\text{- - - - (15)}$$

Differentiating, and dividing both members by $d \log S$,

$$\frac{d \log C}{d \log S} = \frac{n\, d \log (S - \sigma)}{d \log S} \quad\text{- - - - - - - (37)}$$

The first member of this equation is the value of i_1, and i_1 may be substituted for it. Also

$$d \log (S - \sigma) = \frac{dS}{S - \sigma}$$

and

$$d \log S = \frac{dS}{S}$$

Introducing these values in (37) and reducing, we have

$$i_1 = \frac{nS}{S - \sigma} \quad\text{- - - - - - - - - - - - - (38)}$$

The values of n and σ being known for each observational series, it is possible, by means of equation (38), to compute i_1 for any value of S. The values of i_1 have been computed for series of values of S having the uniform interval of 0.2 per cent (and below 1.0 per cent the interval of 0.1 per cent) and having such range in each observational series as to correspond with the range of the observations. These values are recorded in Table 15. It is proposed to discuss their relations to various conditions, beginning with slope.

TABLE 15.—*Values of i_1, the index of relative variation for capacity in relation to slope.*

Conditions of experimentation												
Grade	(A)											
w	0.66			1.00			1.32			1.96		
Q	0.093	0.182	0.545	0.182	0.363	0.734	0.182	0.363	0.734	0.363	0.734	1.119
Parameters of adjusting equation												
σ	0.40	0.20	0.04	0.12	0.07	0.05	0.17	0.10	0.07	0.17	0.10	0.08
b_1	32.2	56.2	150.3	47.4	113.3	252.3	50.1	122.8	282.4	128.9	280.1	397.0
n	1.50	1.60	1.42	1.81	1.70	1.70	1.80	1.53	1.59	1.58	1.40	1.21
S	Values of i_1.											
0.2	....	....	....	....	....	....	....	3.05	....	....	2.79	....
.3	....	....	....	....	....	....	....	2.29	2.08	....	2.09	....
.4	....	....	....	....	2.07	1.94	....	2.04	1.93	2.74	1.86	....
.5	....	....	1.54	2.39	1.98	1.89	2.72	1.91	1.85	2.39	1.74	1.63
.6	....	....	1.52	2.27	1.92	1.85	2.51	1.83	1.80	2.20	1.68	1.57
.7	....	2.24	1.50	2.19	1.89	1.83	2.38	1.78	1.77	2.08	1.63	1.53
.8	....	2.12	1.49	2.13	1.87	1.81	2.28	1.75	1.74	2.00	1.60	1.50
.9	....	2.05	1.48	2.09	1.85	1.80	2.22	1.72	1.72	1.94	1.57	1.48
1.0	....	1.99	1.48	2.06	1.83	1.79	2.17	1.70	1.71	1.90	1.55	1.47
1.2	2.25	1.92	1.47	2.02	1.81	1.78	2.10	1.67	1.69	1.84	1.52	1.44
1.4	2.10	1.86	....	1.99	1.79	....	2.05	1.65	1.68	1.80	....	1.43
1.6	2.00	1.82	....	1.96	1.78	....	1.02	1.63	....	1.76	....	1.42
1.8	1.93	1.79	....	1.95	1.77	....	1.99	1.62	....	1.74	....	1.41
2.0	1.88	....	....	1.93	....	....	1.97	1.61	....	1.72	....	1.40
2.2	1.84	....	....	1.92	....	....	1.95	....	....	....	....	1.39

TABLE 15.—*Values of i_1, the index of relative variation for capacity in relation to slope*—Continued.

Conditions of experimentation												
Grade..	(B)											
w	0.23		0.44		0.66				1.00			
Q	0.093	0.182	0.093	0.182	0.093	0.182	0.363	0.545	0.182	0.393	0.545	0.734
Parameters of adjusting equation: σ	0.70	0.60	0.50	0.10	0.30	0.10	0.08	0.07	0.12	0.08	0.06	0.06
b_1	23.8	33.2	29.7	34 3	19.4	39.8	91.4	132.8	37.6	97.5	157.2	219.3
n	0.93	0.99	1.15	1.63	1.64	1.64	1.45	1.38	1.69	1.54	1.53	1.52
S	Values of i_1.											
0.2	....	....	....	....	....	....	....	2.13	....	2.57	....	2.17
.3	....	....	....	....	....	2.46	....	1.80	....	2.10	....	1.89
.4	....	....	....	....	....	2.19	....	1.68	....	1.93	....	1.78
.5	....	....	....	2.08	....	2.05	1.73	1.61	2.22	1.84	....	1.72
.6	....	....	....	1.96	....	1.97	1.67	1.57	2.11	1.78	....	1.69
.7	....	6.96	4.04	1.90	2.87	1.92	1.64	1.54	2.04	1.74	....	1.66
.8	7.41	3.98	3.08	1.86	2.63	1.88	1.61	1.51	1.98	1.71	1.65	1.64
.9	4.17	2.98	2.60	1.83	2.46	1.85	1.59	1.50	1.95	1.69	1.63	1.62
1.0	3.10	2.49	2.31	1.81	2.34	1.82	1.58	1.49	1.92	1.68	1.62	1.61
1.2	2.22	1.99	1.98	1.78	2.19	1.79	1.55	1.47	1.88	1.65	1.61	1.60
1.4	1.85	1.74	1.80	1.76	2.09	1.77	1.54	1.46	1.85	1.63	1.59	1.58
1.6	1.65	1.59	1.68	1.74	2.02	1.75	1.53	1.45	1.83	1.62	1.58	1.58
1.8	1.52	1.49	1.60	1.73	1.97	1.74	1.52	1.44	1.81	1.61	1.58	1.57
2.0	1.43	....	1.54	....	1.93	1.73	1.51	1.43	1.80	1.60	1.57	....
2.2	1.36	....	1.50	....	1.90	1.72	....	....	1.79	1.60	1.57	....
2.4	....	....	1.46	....	1.88	1.71	....	....	1.78	1.59	....	....
2.6	....	....	1.43	....	1.86	1.71	....	....	1.77	....	....	....
2.8	....	....	....	....	1.84	1.70	....	....	1.76	....	....	....
3.0	....	....	....	....	1.82	1.70	....	....	1.76	....	....	....
3.2	....	....	....	....	....	1.69	....	....	....	....	....	....
3.4	....	....	....	....	....	1.69	....	....	....	....	....	....
3.6	....	....	....	....	....	1.69	....	....	....	....	....	....
3.8	....	....	....	....	....	1.69	....	....	....	....	....	....
4.0	....	....	....	....	....	1.68	....	....	....	....	....	....
4.2	....	....	....	....	....	1.68	....	....	....	....	....	....

Conditions of experimentation												
Grade..	(B)								(C)			
w	1.32				1.96				0.44		0.66	
Q	0.182	0.363	0.545	0.734	0.363	0.545	0.734	1.119	0.093	0.182	0.093	0.182
Parameters of adjusting equation: σ	0.17	0.12	0.10	0.08	0.18	0.14	0.12	0.10	0.40	0.20	0.16	0.11
b_1	39.5	96.5	165.4	233.5	93.9	153.5	228.2	363.3	22.6	34.4	18.2	38.6
n	1.61	1.54	1.55	1.57	1.64	1.60	1.46	1.43	1.43	1.50	1.58	1.54
S	Values of i_1.											
0.2	....	....	....	....	....	....	....	2.86	....	....	....	....
.3	....	2.56	....	2.14	....	....	2.44	2.15	....	....	....	2.43
.4	2.80	2.20	....	1.96	2.99	....	2.09	1.91	....	....	....	2.12
.5	2.44	2.02	1.94	1.87	2.57	2.23	1.93	1.79	....	....	2.33	1.97
.6	2.25	1.92	1.86	1.81	2.35	2.09	1.83	1.73	4.29	2.22	2.16	1.88
.7	2.13	1.85	1.81	1.78	2.21	2.01	1.77	1.68	3.39	2.10	2.05	1.83
.8	2.05	1.81	1.78	1.75	2.12	1.94	1.72	1.64	2.86	2.00	1.98	1.79
.9	1.99	1.77	1.75	1.72	2.06	1.90	1.69	1.62	2.57	1.93	1.92	1.75
1.0	1.94	1.75	1.73	1.71	2.01	1.86	1.66	1.60	2.39	1.88	1.87	1.73
1.2	1.88	1.71	1.70	1.68	1.94	1.82	1.63	1.57	2.15	1.81	1.82	1.70
1.4	1.84	1.68	1.67	1.67	1.89	1.78	1.60	....	2.00	1.76	1.79	1.67
1.6	1.80	1.66	1.66	1.65	1.85	1.76	1.58	....	1.91	1.72	1.76	1.65
1.8	1.78	1.64	1.65	1.64	1.83	1.74	1.57	....	1.84	1.69	1.74	1.64
2.0	1.76	1.63	....	....	1.81	....	1.56	....	1.79	1.67	1.72	1.63
2.2	1.75	1.62	....	....	1.79	....	....	....	1.75	1.65	1.70	1.62
2.4	1.74	....	....	....	....	....	....	....	....	....	1.69	1.61
2.6	1.73	....	....	....	....	....	....	....	....	....	1.69	1.61
2.8	....	....	....	....	....	....	....	....	....	....	1.68	1.60
3.0	....	....	....	....	....	....	....	....	....	....	1.67	1.60
3.2	....	....	....	....	....	....	....	....	....	....	1.66	1.59
3.4	....	....	....	....	....	....	....	....	....	....	1.66	1.59
3.6	....	....	....	....	....	....	....	....	....	....	1.65	1.59
3.8	....	....	....	....	....	....	....	....	....	....	1.65	1.59
4.0	....	....	....	....	....	....	....	....	....	....	1.65	....
4.2	....	....	....	....	....	....	....	....	....	....	1.64	....

TABLE 15.—*Values of i_1, the index of relative variation for capacity in relation to slope*—Continued.

Conditions of experimentation	Grade..	(C)											
	w......	0.66			1.00					1.32			
	Q......	0.363	0.545	0.734	0.182	0.363	0.545	0.734	1.119	0.182	0.363	0.545	0.734
Parameters of adjusting equation	σ.......	0.08	0.06	0.04	0.15	0.11	0.09	0.07	0.06	0.22	0.16	0.13	0.11
	b_1......	82.9	122.8	162.1	40.4	100.1	159.2	199.2	301.6	33.7	99.9	156.1	218.5
	n.......	1.46	1.48	1.50	1.59	1.41	1.33	1.35	1.39	1.85	1.40	1.35	1.30
S		Values of i_1.											
0.2			2.12			3.14		2.18					2.90
.3			1.86			2.23		1.76			3.00		2.12
.4		1.83	1.75		2.54	1.95		1.64			2.33		1.80
.5		1.74	1.69	1.63	2.27	1.81	1.63	1.57	1.58		2.06		1.67
.6		1.68	1.65	1.61	2.12	1.73	1.57	1.53	1.55	2.92	1.91	1.72	1.60
.7		1.65	1.62	1.59	2.02	1.68	1.53	1.50	1.52	2.70	1.82	1.65	1.55
.8		1.62	1.60	1.58	1.95	1.64	1.50	1.48	1.50	2.55	1.75	1.61	1.51
.9		1.60	1.59	1.57	1.90	1.61	1.48	1.46	1.49	2.45	1.70	1.57	1.49
1.0		1.59	1.58	1.57	1.87	1.59	1.47	1.45	1.48	2.37	1.67	1.55	1.47
1.2		1.56	1.56		1.81	1.55	1.44	1.43	1.46	2.27	1.61	1.51	1.44
1.4		1.55	1.55		1.78	1.53	1.43	1.42	1.45	2.20	1.58	1.49	1.42
1.6		1.54	1.54		1.75	1.51	1.42	1.41		2.14	1.55	1.47	1.40
1.8		1.53	1.54		1.73	1.50	1.41	1.41		2.11	1.54	1.45	1.39
2.0		1.52	1.53		1.71	1.49	1.40	1.40		2.08	1.52	1.44	1.38
2.2		1.52	1.53		1.70	1.49	1.39	1.39		2.06	1.51	1.43	1.37
2.4		1.51			1.69	1.48				2.04	1.50	1.42	
2.6		1.51			1.68	1.47							
2.8					1.68	1.47							
3.0													
3.2													
3.4													
3.6													
3.8													

Conditions of experimentation	Grade..	(C)				(D)						
	w......	1.96				0.66			1.00			
	Q......	0.363	0.545	0.734	1.119	0.093	0.182	0.545	0.182	0.363	0.545	0.734
Parameters of adjusting equation	σ.......	0.24	0.20	0.17	0.14	0.19	0.14	0.08	0.17	0.12	0.10	0.08
	b_1......	93.4	155.7	245.1	438.3	13.2	37.2	115.2	32.8	87.9	129.4	174.6
	n.......	1.62	1.50	1.34	1.59	1.80	1.55	1.51	1.67	1.49	1.68	1.52
S		Values of i_1.										
0.2								2.52				2.54
.3								2.06		2.48		2.12
.4				2.33			2.38	1.89		2.12		1.90
.5		3.12	2.49	2.03	2.21		2.15	1.80		1.95	2.11	1.81
.6		2.71	2.24	1.87	2.07	2.64	2.02	1.74		1.86	2.04	1.75
.7		2.47	2.09	1.77	1.99	2.47	1.93	1.71	2.20	1.80	1.97	1.72
.8		2.32	1.99	1.70	1.93	2.36	1.88	1.68	2.12	1.75	1.93	1.69
.9		2.21	1.92	1.65	1.88	2.28	1.83	1.66	2.06	1.71	1.90	1.67
1.0		2.14	1.87	1.62	1.85	2.22	1.80	1.64	2.01	1.69	1.87	1.65
1.2		2.03	1.79	1.56	1.80	2.14	1.75	1.62	1.94	1.65	1.84	1.63
1.4		1.96	1.74	1.53		2.08	1.72	1.60	1.90	1.63	1.81	1.61
1.6		1.91	1.71	1.50		2.04	1.70	1.59	1.86	1.61	1.80	1.60
1.8		1.87	1.68			2.01	1.68	1.58	1.84	1.59	1.79	1.59
2.0		1.84	1.66			1.99	1.66	1.57	1.82	1.58	1.78	
2.2		1.82	1.65			1.97	1.65	1.57	1.81	1.57		
2.4						1.96	1.64		1.80	1.56		
2.6						1.94	1.63		1.79			
2.8									1.78			

TABLE 15. —*Values of i_1, the index of relative variation for capacity in relation to slope*—Continued.

Conditions of experimentation	Grade..	(D)		(E)								
	w......	1.32		0.66		1.00				1.32		
	Q......	0.363	0.734	0.363	0.734	0.182	0.363	0.734	1.119	0.363	0.734	1.119
Parameters of adjusting equation	σ......	0.16	0.11	0.16	0.11	0.08	0.06	0.04	0.03	0.04	0.03	0.02
	b_1......	80.1	160.0	33.8	50.2	17.0	37.3	76.5	145.9	38.8	76.1	126.1
	n......	1.77	1.65	1.93	1.73	1.72	1.70	1.58	1.58	1.57	1.50	1.77
s		Values of i_1.										
0.2							2.43	1.98				
.3			2.60				2.13	1.83				
.4			2.27			2.16	2.00	1.76				
.5		2.60	2.11			2.06	1.93	1.72	1.69		1.59	
.6		2.41	2.02			1.99	1.89	1.69	1.67	1.68	1.57	1.83
.7		2.29	1.95			1.95	1.86	1.68	1.65	1.67	1.56	1.82
.8		2.21	1.91			1.92	1.84	1.67	1.64	1.66	1.55	1.82
.9		2.15	1.88			1.90	1.82	1.66	1.64	1.65	1.55	1.81
1.0		2.11	1.85	2.09	2.17	1.88	1.81	1.65	1.63	1.64	1.54	1.81
1.2		2.04	1.81	2.03	2.13	1.85	1.79	1.64	1.62	1.63	1.54	1.80
1.4		2.00		1.99	2.10	1.83	1.78	1.63	1.62	1.62		
1.6		1.97			2.08	1.82	1.77	1.62	1.61	1.61		
1.8		1.94				1.81	1.76	1.62	1.61	1.61		
2.0		1.92				1.80	1.76	1.61	1.61	1.60		
2.2						1.79	1.75		1.61			
2.4						1.79	1.75		1.60			
2.6						1.78						
2.8						1.78						

Conditions of experimentation	Grade..	(F)										(G)
	w......	0.66			1.00				1.32			0.66
	Q......	0.182	0.363	0.734	0.182	0.363	0.734	1.119	0.363	0.734	1.119	0.363
Parameters of adjusting equation	σ......	0.33	0.21	0.17	0.44	0.31	0.22	0.17	0.39	0.28	0.23	0.50
	b_1......	12.02	30.5	52.2	7.96	28.2	65.0	106.9	30.3	71.1	126.4	27.5
	n......	1.86	1.69	1.61	2.31	1.88	1.61	1.60	1.63	1.73	1.49	1.74
s		Values of i_1.										
0.2												
.3												
.4												
.5												
.6												
.7							2.35	2.08				
.8						3.07	2.22	2.00		2.65	2.09	
.9				1.98		2.87	2.13	1.94		2.50	2.00	
1.0			2.14	1.94		2.72	2.06	1.90		2.40	1.94	3.48
1.2		2.57	2.04	1.88	3.65	2.54	1.98	1.83	2.42	2.25	1.85	2.98
1.4		2.44	1.99	1.83	3.38	2.42	1.91	1.79	2.27	2.15	1.78	2.71
1.6		2.35	1.94	1.80	3.20	2.33	1.87	1.76	2.16	2.09	1.74	2.53
1.8		2.28	1.91	1.78	3.07	2.27	1.84	1.74	2.08		1.71	2.41
2.0		2.23	1.89		2.97	2.23			2.03			2.32
2.2		2.19			2.90	2.19			1.99			2.25
2.4		2.16			1.84	2.16						2.20
2.6		2.14			1.79	2.14						2.16
2.8												2.12
3.0												2.08

TABLE 15.—*Values of i_1, the index of relative variation for capacity in relation to slope*—Continued.

Conditions of experimentation	Grade	(G)								(H)		
	w	0.66		1.00			1.32			0.66		
	Q	0.734	1.119	0.363	0.734	1.119	0.363	0.734	1.119	0.363	0.734	1.119
Parameters of adjusted equation	σ	0.36	0.28	0.58	0.41	0.33	0.71	0.50	0.40	0.80	0.56	0.48
	b_1	64.5	85.0	23.6	65.7	115.5	15.39	62.3	114.5	19.38	52.9	75.1
	n	1.69	1.78	1.85	1.70	1.63	2.37	1.71	1.54	2.01	1.72	1.67
S		Values of i_1.										
0.2		....	....	....	....	....	....	....	....	....	....	....
.3		....	....	....	....	....	....	....	....	....	....	....
.4		....	....	....	....	....	....	....	....	....	....	....
.5		....	....	....	....	....	....	....	....	....	....	....
.6		....	3.23	....	....	3.63	....	....	....	....	....	....
.7		3.49	2.89	....	4.11	3.09	....	....	3.61	....	....	5.31
.8		3.08	2.68	....	3.49	2.78	....	4.58	3.09	....	5.75	4.17
.9		2.82	2.54	....	3.12	2.58	....	3.86	2.78	....	4.56	3.58
1.0		2.65	2.43	....	2.88	2.44	....	3.43	2.57	....	3.92	3.21
1.2		2.42	2.29	3.57	2.58	2.25	....	2.94	2.32	6.03	3.23	2.78
1.4		2.28	2.20	3.15	2.40	2.14	....	2.64	2.16	4.69	2.88	2.54
1.6		2.19	2.14	2.90	2.29	2.06	....	2.49	2.06	4.02	2.65	2.38
1.8		2.12	2.09	2.71	2.20	2.00	3.91	2.38	1.99	3.62	2.50	2.27
2.0		2.07	2.05	2.60	2.14	1.96	3.67	2.29	1.93	3.35	2.40	2.20
2.2		2.03	2.02	2.51	2.09	1.92	3.50	2.22	1.89	3.16	2.32	2.14
2.4		1.99	2.00	2.43	2.05	1.89	3.36	2.17	1.85	3.01	2.25	2.09
2.6		1.96	1.98	2.38	2.02	....	3.26	2.12	1.83	2.90	2.20	2.05
2.8		....	....	2.33	....	....	3.18	2.08	....	2.81	2.16	....
3.0		....	....	2.29	....	....	3.11	....	....	....	2.12	....
3.2		....	....	....	....	....	3.05	....	....	....	2.09	....
3.4		....	....	....	....	....	3.00	....	....	....	....	....

VARIATION OF THE INDEX.

Each column of the table contains a set of values of i_1 which pertain to the same grade, fineness, width, and discharge and of which the changes are related to slope only. In figure 31 a number of these sets are plotted in relation to slope. The curves have a strong family likeness, arising from the fact that the data were all adjusted by the sigma formula; but the likeness would not altogether disappear if the assumptions of that formula were abandoned. The general relations of the index to slope are as follows:

(1) It varies decreasingly with slope.

(2) Its rate of change is greater for low slopes than for high.

The upper group of curves all pertain to grade (C) and width 1.00 foot, but represent different discharges. They show (3) that the rate of change for similar slopes is greater for small discharges than for large.

The second group of curves all pertain to grade (C) and discharge 0.363 ft.^{3}/sec., but represent different widths. They show (4) that the rate of change for similar slopes is greater for broad channels than for narrow, or, as the depth varies inversely with the width, that the rate of change is greater for shallow streams than for deep.

The third group of curves all pertain to width 1.00 foot and discharge 0.363 ft.^{3}/sec., but represent different grades of débris. They show (5) that the rate of change is greater for coarse débris than for fine.

In the third group the curves for grades (A), (B), (C), (D), and (E) lie close together, while those for the coarser grades (F) and (G) are well separated. This is probably connected with the fact that the range of fineness gradually increases from (A) to (E) and then drops abruptly from (E) to (F). The influence of increasing range approximately neutralizes that of decreasing fineness, and the inference is (6) that the rate of change in the index is greater for small range than for large.

Consider now the variations of the index in relation to width. In figure 32 (p. 106) the ordinates, as before, represent values of i_1 and the abscissas represent width of channel. The points fixed by the data are shown by the dots.

(7) The upper group of curves all pertain to grade (C) and discharge 0.182 ft.^{3}/sec., but represent different slopes. Their common char-

acter is a distinct minimum. From the neighborhood of width 0.66 foot there is increase of i_1 in the direction of greater width, and also in the direction of less width.

(8) The position of the minimum is apparently the same for low slopes as for high.

(9) The minimum is most strongly marked in case of the gentler slopes.

The second group of curves all pertain to grade (C) and a slope of 1.0 per cent but differ in respect to discharge. Each of them shows a minimum, except the curve for discharge 0.093 ft.³/sec., which has but two fixed points. They show also that—

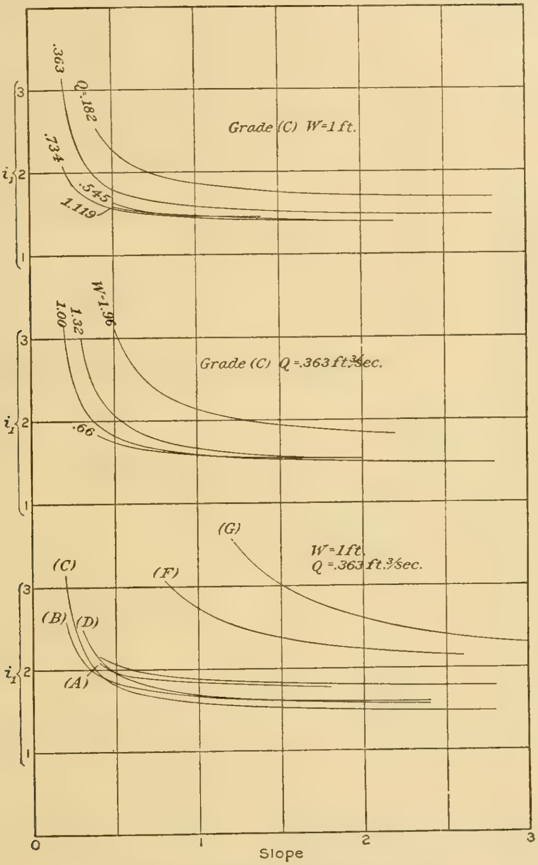

FIGURE 31.—Variations of i_1 in relation to slope.

(10) The position of the minimum is related to discharge. For large discharges it is associated with relatively large widths, for smaller discharges with smaller widths.

(11) The minimum is more pronounced, or the associated rates of change in the index are higher in case of small discharge than of large.

Various analogies, which appear in another part of this paper, render it probable that all the preceding inferences are of a general character; but those in regard to width are not sustained by all the data.

The curves of the third group are based on observations with grade (B) and are drawn, like those of the first group, to contrast the relations of the index to width for different slopes. With the gentler slopes they give indications of a minimum, but not with the steeper. The character of the discrepancy is such as to suggest that the values of the index computed for width 0.23 foot vary too rapidly with slope; and this result might be brought about by assigning too large a value to σ. A critical review of the data, however, failed to find warrant for any material change in that constant.

It is believed that a group of discrepancies which this instance illustrates are connected with the history of the experimental work. The first grade to be investigated was (B), and the methods of manipulation were subject to various minor changes, which were not always recorded; but the range of conditions was large. Grade (C) was next taken up, and again the range of conditions was large. Other grades followed, with less elaborate range of conditions; but the work on grade (G) was somewhat expanded, in order to learn the influence of coarser débris on various factors. The work on (G) also had the advantage of the fullest development of experimental method as well as that of uniformity of method. Because of this history it is believed that the results for grades (C) and (G) are of higher authority than those of other grades; and the belief is strengthened by the general symmetry and internal consistency of the (C) and (G) results. The inferences, given in preceding paragraphs, from data of grades (C) and (G) are therefore accepted, and the discordance of data for grade (B), while not specifically explained, is ascribed in a general way to unrecorded differences in laboratory methods.

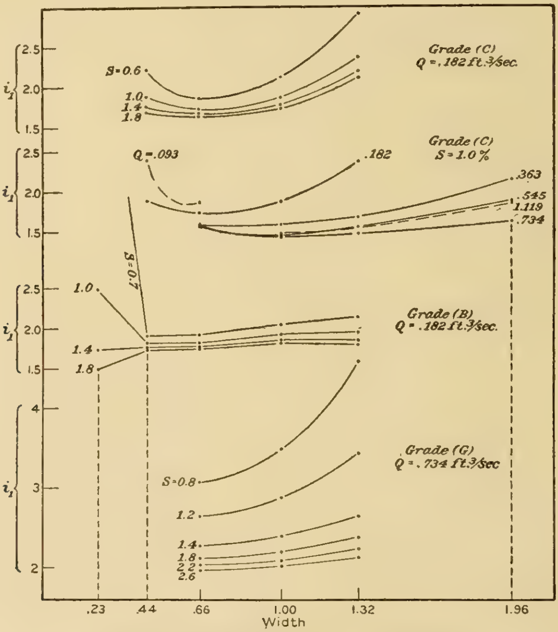

FIGURE 32.—Variations of i_1 in relation to width of channel.

The curves of the fourth group of figure 32 all pertain to grade (G) and discharge 0.734 ft.³/sec. but differ in respect to slope. Compared with the first and second groups they are seen to be consistent with the inference as to a minimum value of i_1, but the minimum falls outside the range of widths for which data were obtained. With grade (C) and discharge 0.734 ft.³/sec. the minimum falls between widths 1 foot and 1.32 feet, but nearer to the former. With grade (G) and the same discharge it apparently falls with some width less than 0.66 foot. This indicates that—

(12) The position of the minimum is related to fineness. For the finer débris it is associated with relatively great width; for the coarser, with smaller width.

The curves of the fourth group support the ninth inference, that the minimum is most strongly marked for the gentlest slope.

In the study of the data many other comparisons of the influence of width were made, but they are not here illustrated. Their chief service was in indicating the comparative value of different divisions of the body of data. The general fact brought out—and one emphasized in various other ways—is that the measures of precision derived from discrepancies of observations within a single series by no means cover the whole field. The discrepancies discovered when properties of different series are compared are quite as important and must be given consideration in connection with the broader generalizations.

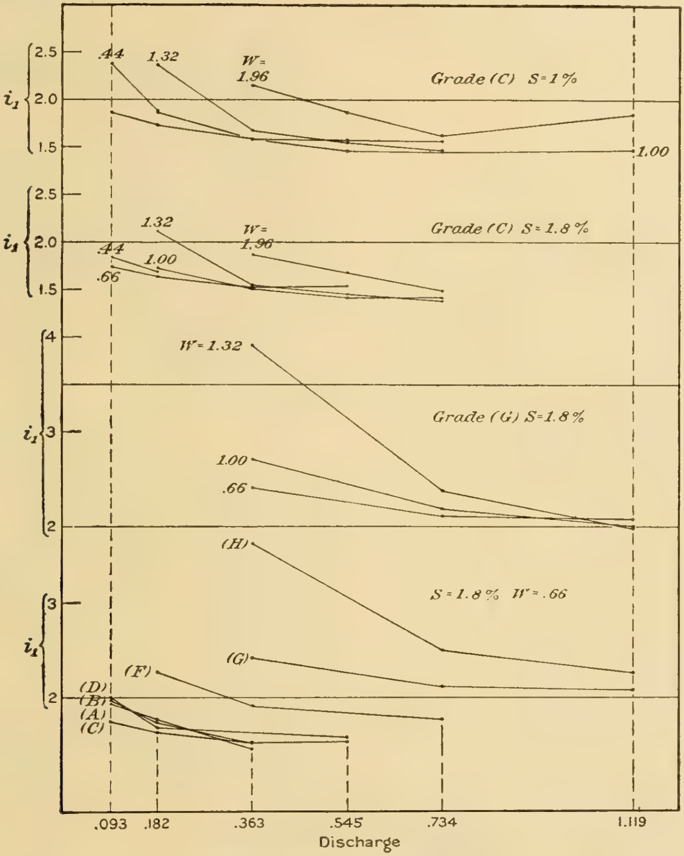

FIGURE 33.—Variations of i_1 in relation to discharge.

Let us now consider the relations of the varying value of i_1 to discharge. These are illustrated by figure 33. The curves of the upper group all pertain to grade (C) and slope 1.0 per cent but differ in respect to width of channel. Those of the second group pertain to grade (C) and slope 1.8 per cent; those of the third group to grade (G) and slope 1.8 per cent. The general fact is that—

(13) As discharge increases the value of i_1 diminishes. There are three exceptions, of which

two do not exceed the computed probable errors of the data, and the third is connected with a value of i_1 to which the lowest weight is ascribed.

(14) The rate of change in the index is greater for small discharges than for large.

(15) For the same discharges the rate of change in the index is greater for wide channels than for narrow, and is therefore greater for shallow streams than for deep.

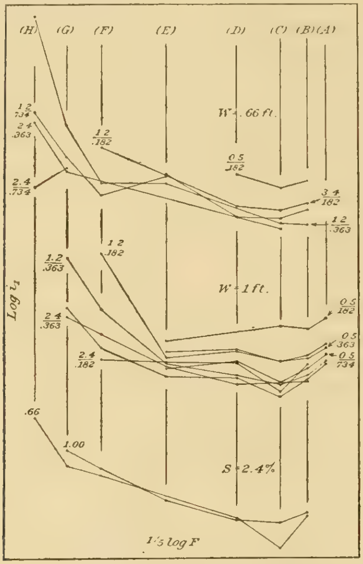

FIGURE 34.—Variations of i_1 in relation to fineness of débris.

The curves of the lowest group all pertain to width 0.66 foot and slope 1.8 per cent, but differ as to grade of débris. They indicate that—

(16) The rate of change in the index is greater for coarse débris than for fine. The peculiarities of spacing, as in a previous instance, may show the influence of the factor of range in fineness within the several grades.

To consider now the relations of the values of i_1 to the fineness of débris, the comparison is made with linear fineness—instead of bulk fineness, as in discussing σ, and it is found convenient to plot the logarithms of the quantities instead of the quantities themselves. In figure 34 the curves of the upper group are derived from experiments conducted with a trough width of 0.66 foot, and each one pertains to a particular combination of slope and discharge. Those of the second group are derived from experiments with a trough width of 1 foot.

(17) In the main they show decrease of i_1 with increase of fineness, but the finer grades give the opposite indication. The data are not sufficiently harmonious to determine whether the law of change is continuous or involves a reversal. If it is continuous, i_1 is an inverse function of F.

In view of the fact that the double variation of i_1 in relation to width is a complicating factor and of the further fact that that variation is less pronounced with high slopes than with low, two curves (the lowest group of fig. 34) were constructed from data pertaining to the highest practicable slope, 2.4 per cent. Each curve belongs to a particular width of trough, and each is a composite with respect to discharge. Their indication is practically the same as that of the other groups.[1]

The character of the material has not seemed to warrant a quantitative discussion of the variations of the index of variation, and a summary of the qualitative discussion is necessarily limited to generalities. The index of relative variation or the sensitiveness of capacity for traction to change of slope is a decreasing function of the slope, the discharge, the fineness of débris, and the range of fineness and is a minimum function of width of channel. In symbols,

$$i_1 = f(\grave{S}, \grave{Q}, \grave{F}, \grave{H}, \breve{w}) \quad \text{--------} (39)$$

If we assume tentatively that the function replacing i_1 in the exponent is the product of functions of the individual conditions—that is, if we write

$$i_1 = (f_{\mathrm{I}}(S))\ (f_{\mathrm{II}}(Q))\ (f_{\mathrm{III}}(F))\ (f_{\mathrm{IV}}(H))\ (f_{\mathrm{V}}w))$$

then we must also recognize that in $f_{\mathrm{I}}(S)$, f_{I} is itself a function of Q, F, H, and w, that f_{II} is a function of F and w, and that f_{V} is a function of

---

[1] In the data on flume traction the relation of capacity to fineness exhibits peculiarities quite analogous to those here found in the relation of i_1 to fineness. The capacity is larger for very fine and very coarse débris than for intermediate grades. A tentative explanation (see Chapter XII) connects the larger capacity for fine débris with a transition in process from traction to suspension.

S, *Q*, and *F*. Parallel complexities would also arise if attempt were made to formulate the relations by means of such an expression as

$$i_1 = f_{\mathrm{I}}(S) + f_{\mathrm{II}}(Q) + f_{\mathrm{III}}(F) + f_{\mathrm{IV}}(H) + f_{\mathrm{V}}(w)$$

The sensitiveness of capacity to slope appears to be a function of the conditions jointly rather than severally.

The development of complexity within complexity suggests that the actual nature of the relation is too involved for disentanglement by empiric methods, but that conclusion does not necessarily follow. Just as a highly complex mathematical expression may be the exact equivalent of a fairly simple expression of a different type, so a physical law may defy formulation when approached in a certain way yet yield readily when the best method of approach has been discovered.

FORMULATION WITH CONSTANT COEFFICIENT.

For the relation of capacity to slope the formula equivalent to (34) is

$$C = c_1 S^{j_1} \quad \text{.............} (40)$$

in which the constant coefficient c_1 is the value of capacity when $S=1$.

From equation (10) (p. 96),

$$c_1 = b_1 (1-\sigma)^n \quad \text{...........} (41)$$

Also as (10) and (40) give equivalent expressions for *C*, we may equate their second members:

$$c_1 S^{j_1} = b_1 (S-\sigma)^n$$

Substituting the value of c_1 from (41),

$$b_1 (1-\sigma)^n \, S^{j_1} = b_1 (S-\sigma)^n$$

whence

$$S^{j_1} = \left(\frac{S-\sigma}{1-\sigma}\right)^n$$

and

$$j_1 = n \frac{\log (S-\sigma) - \log (1-\sigma)}{\log S} \quad \text{......} (42)$$

By means of this formula the values of j_1 in Table 16 were computed. These values have been subjected to systematic comparison with the associated conditions (*S*, *Q*, *w*, etc.) in the same manner as were the values of the exponent i_1; but the results of the comparison need not be given in detail because they are parallel to those for i_1. They are in fact identical so far as verbal statement is concerned and differ only in quantitative ways. It is true in the main, and almost without exception, that the variations of j_1 are less rapid than those of i_1; and their average range is about half as great.

TABLE 16.—*Values of j_1, in $C=c_1S^{j_1}$, the coefficient c_1 being a constant.*

Conditions of experimentation: Grade	(A)											
w	0.66			1.00			1.32			1.96		
Q	0.093	0.182	0.545	0.182	0.363	0.734	0.182	0.363	0.734	0.363	0.734	0.119
c_1	15	39.4	142	37.6	100	231	36.5	104	252	96.1	242	359
S	Values of j_1.											
0.2								2.09			1.91	
.4					1.93	1.85		1.86	1.80	2.21	1.68	1.39
.6			1.50	2.15	1.88	1.82	2.32	1.76	1.75	2.03	1.61	1.35
.8		2.06	1.49	2.10	1.85	1.80	2.23	1.72	1.73	1.96	1.57	1.33
1.0		1.99	1.48	2.06	1.83	1.79	2.17	1.70	1.71	1.90	1.55	1.31
1.2	2.36	1.95	1.47	2.04	1.82	1.78	2.13	1.68	1.70	1.87	1.54	
1.4	2.27	1.93		2.02	1.81		2.10	1.67	1.68	1.84		
1.6	2.20	1.91		2.01	1.80		2.08	1.66		1.82		
1.8	2.16	1.88		2.00	1.80		2.06	1.65		1.81		
2.0	2.12			1.99			2.05	1.65		1.80		
2.2	2.09			1.99			2.04					

TABLE 16.—*Values of j_1, in $C=c_1S^{j_1}$, the coefficient c_1 being a constant*—Continued.

Conditions of experimentation: Grade	(B)											
w	0.23		0.44		0.66				1.00			
Q	0.093	0.182	0.093	0.182	0.093	0.182	0.363	0.545	0.182	0.363	0.545	0.734
c_1	7.8	13.4	13.3	28.9								
S	Values of j_1.											
0.2								1.69		1.95		1.79
.4						1.96		1.57		1.78		1.68
.6				1.88		1.89	1.63	1.53	2.00	1.73		1.64
.8	4.57	3.09	2.63	1.84	2.47	1.85	1.60	1.50	1.95	1.70	1.64	1.62
1.0	3.10	2.49	2.31	1.81	2.34	1.82	1.58	1.49	1.92	1.68	1.62	1.61
1.2	2.60	2.21	2.16	1.79	2.26	1.81	1.56	1.48	1.90	1.66	1.61	1.61
1.4	2.34	2.05	2.02	1.78	2.20	1.80	1.55	1.47	1.88	1.65	1.61	1.60
1.6	2.18	1.94	1.94	1.77	2.16	1.79	1.54	1.46	1.87	1.64	1.60	1.59
1.8	2.05	1.86	1.88	1.77	2.13	1.78	1.54	1.46	1.86	1.64	1.60	1.59
2.0	1.96		1.83		2.10	1.77	1.53	1.45	1.85	1.64	1.59	
2.2	1.89		1.79		2.08	1.77			1.84	1.63	1.59	
2.4			1.76		2.06	1.76			1.84	1.63		
2.6			1.73		2.04	1.76			1.83			
2.8					2.03	1.75			1.83			
3.0					2.02	1.75			1.82			
3.2						1.75						
3.4						1.75						
3.6						1.74						
3.8						1.74						
4.0						1.74						
4.2						1.74						

Conditions of experimentation: Grade	(B)								(C)			
w	1.32				1.96				0.44		0.66	
Q	0.182	0.363	0.545	0.734	0.363	0.545	0.734	1.119	0.093	0.182	0.093	0.182
c_1	29.2	79.3	140	205	67.8	120	189	312	10.9	24.7	13.8	32.3
S	Values of j_1.											
0.2								1.96				
.4	2.26	1.92		1.81	2.36		1.82	1.69				1.88
.6	2.08	1.82	1.79	1.76	2.16	1.98	1.74	1.65	3.08	2.05	2.00	1.80
.8	2.00	1.78	1.75	1.73	2.06	1.91	1.70	1.62	2.60	1.95	1.93	1.76
1.0	1.94	1.75	1.73	1.71	2.01	1.87	1.66	1.60	2.39	1.88	1.88	1.73
1.2	1.92	1.72	1.71	1.69	1.97	1.84	1.64	1.58	2.26	1.83	1.85	1.71
1.4	1.89	1.71	1.70	1.68	1.94	1.82	1.63		2.17	1.80	1.83	1.70
1.6	1.87	1.70	1.69	1.67	1.92	1.81	1.62		2.11	1.77	1.81	1.69
1.8	1.85	1.69	1.68	1.67	1.90	1.80	1.61		2.06	1.76	1.80	1.68
2.0	1.84	1.68			1.89		1.61		2.03	1.75	1.79	1.67
2.2	1.83	1.68			1.88				1.99	1.74	1.78	1.67
2.4	1.82										1.77	1.66
2.6	1.82										1.76	1.66
2.8											1.76	1.66
3.0											1.75	1.65
3.2											1.75	1.65
3.4											1.75	1.65
3.6											1.74	1.64
3.8											1.74	1.64
4.0											1.74	
4.2											1.73	

Table 16.—*Values of j_1, in $C=c_1S^{j_1}$, the coefficient c_1 being a constant*—Continued.

Conditions of experimentation												
Grade	(C)											
w	0.66			1.00					1.32			
Q	0.363	0.545	0.734	0.182	0.363	0.545	0.734	1.119	0.182	0.363	0.545	0.734
c_1	73.4	112	153	31.2	84.9	140	181	277	21.3	78.4	130	184
S	Values of j_1.											
0.2	....	1.76	....	....	2.03	....	1.65	....	....	....	....	1.86
.4	1.68	1.65	....	2.12	1.73	....	1.53	1.55	....	1.92	....	1.60
.6	1.63	1.61	1.58	1.98	1.66	1.51	1.49	1.51	2.61	1.78	1.62	1.54
.8	1.61	1.59	1.58	1.91	1.62	1.49	1.47	1.49	2.46	1.71	1.58	1.49
1.0	1.59	1.58	1.57	1.87	1.59	1.47	1.45	1.48	2.37	1.67	1.55	1.47
1.2	1.58	1.57	....	1.84	1.57	1.46	1.44	1.47	2.32	1.64	1.53	1.45
1.4	1.57	1.56	....	1.82	1.56	1.45	1.43	1.47	2.28	1.62	1.51	1.44
1.6	1.56	1.56	....	1.80	1.55	1.44	1.43	....	2.25	1.60	1.50	1.43
1.8	1.55	1.55	....	1.79	1.54	1.43	1.42	....	2.23	1.59	1.49	1.42
2.0	1.55	1.55	....	1.78	1.53	1.42	1.42	....	2.21	1.58	1.49	1.42
2.2	1.54	1.55	....	1.77	1.53	1.42	1.42	....	2.19	1.57	1.48	1.41
2.4	1.54	....	....	1.76	1.52	....	....	....	2.17	1.56	1.47	....
2.6	1.54	....	....	1.76	1.52	....	....	....	....	....	....	....
2.8	....	....	....	1.75	1.51	....	....	....	....	....	....	....

Conditions of experimentation											
Grade	(C)				(D)						
w	1.96				0.66			1.00			
Q	0.363	0.545	0.734	1.119	0.093	0.182	0.545	0.182	0.363	0.545	0.734
c_1	59.8	111	191	345	9.1	29.5	102	24.0	72.5	108	154
S	Values of j_1.										
0.2	....	....	....	....	....	....	1.91	....	....	....	1.92
.4	....	....	1.88	....	....	2.02	1.74	....	1.84	....	1.75
.6	2.38	2.03	1.73	1.95	2.41	1.90	1.69	....	1.77	1.94	1.70
.8	2.22	1.94	1.66	1.89	2.29	1.84	1.66	2.06	1.72	1.90	1.67
1.0	2.14	1.87	1.62	1.85	2.22	1.80	1.64	2.01	1.69	1.87	1.65
1.2	2.08	1.83	1.60	1.82	2.18	1.78	1.63	1.98	1.67	1.85	1.64
1.4	2.04	1.80	1.58	....	2.15	1.76	1.62	1.95	1.65	1.84	1.63
1.6	2.01	1.78	1.56	....	2.12	1.74	1.61	1.93	1.64	1.84	1.63
1.8	1.99	1.76	....	....	2.10	1.73	1.61	1.91	1.63	1.83	1.62
2.0	1.97	1.75	....	....	2.09	1.72	1.60	1.90	1.63	1.82	....
2.2	1.95	1.74	....	....	2.08	1.71	1.60	1.89	1.62	1.82	....
2.4	....	....	....	....	2.07	1.71	....	1.88	1.61	....	....
2.6	....	....	....	....	2.03	1.70	....	1.87	....	....	....
2.8	....	....	....	....	....	....	....	1.87	....	....	....

Conditions of experimentation											
Grade	(D)		(E)								
w	1.32		0.66		1.00				1.32		
Q	0.373	0.734	0.363	0.734	0.182	0.363	0.734	1.119	0.363	0.734	1.119
c_1	58.9	132	24.8	40.1	14.7	33.6	71.5	139	36.4	72.6	122
S	Values of j_1.										
0.2	....	....	....	....	....	2.03	1.76	....	....	....	....
.4	....	2.02	....	....	1.99	1.89	1.70	....	....	....	....
.6	2.25	1.93	....	....	1.94	1.85	1.68	1.65	1.66	1.56	1.82
.8	2.16	1.88	....	....	1.98	1.82	1.66	1.64	1.65	1.55	1.81
1.0	2.11	1.85	2.09	2.17	1.88	1.81	1.65	1.63	1.64	1.54	1.81
1.2	2.07	1.83	2.06	2.15	1.86	1.80	1.64	1.63	1.63	1.54	1.80
1.4	2.05	....	2.03	2.13	1.85	1.79	1.64	1.62	1.62	....	....
1.6	2.03	....	....	2.12	1.85	1.79	1.63	1.62	1.62	....	....
1.8	2.02	....	....	....	1.84	1.78	1.63	1.62	1.62	....	....
2.0	2.01	....	....	....	1.84	1.78	1.63	1.62	1.62	....	....
2.2	....	....	....	....	1.83	1.77	....	1.62	....	....	....
2.4	....	....	....	....	1.83	1.77	....	1.62	....	....	....
2.6	....	....	....	....	1.82	....	....	....	....	....	....
2.8	....	....	....	....	1.82	....	....	....	....	....	....

TABLE 16.—*Values of j_1, in $C=c_1S^{j_1}$, the coefficient c_1, being a constant*—Continued.

Conditions of experimentation: Grade	(F)										(G)
Conditions of experimentation: w	0.66			1.00				1.32			0.66
Conditions of experimentation: Q	0.182	0.363	0.734	0.182	0.363	0.734	1.119	0.363	0.734	1.119	0.363
c_1	5.7	20.4	38.7	2.1	13.9	43.6	79.6	13.5	40.3	86.5	8.3
S	Values of j_1.										
0.2											
.4											
.6											
.8					2.85	2.14	1.95		2.52	2.01	
1.0		2.14	1.94		2.73	2.06	1.90		2.40	1.94	3.48
1.2	2.67	2.08	1.91	3.87	2.65	2.02	1.87	2.54	2.32	1.88	3.21
1.4	2.60	2.05	1.88	3.71	2.58	1.98	1.84	2.45	2.27	1.85	3.04
1.6	1.53	2.03	1.86	3.59	2.52	1.95	1.82	2.38	2.22	1.83	2.91
1.8	2.47	2.01	1.85	3.50	2.48	1.94	1.81	2.33		1.80	2.82
2.0	2.43	1.99		3.43	2.45			2.29			2.76
2.2	2.41			3.36	2.42			2.26			2.70
2.4	2.39			3.31	2.39						2.65
2.6	2.38			3.27	2.37						2.61
2.8											2.58
3.0											2.55

Conditions of experimentation: Grade	(G)								(H)		
Conditions of experimentation: w	0.66		1.00			1.32			0.66		
Conditions of experimentation: Q	0.734	1.119	0.363	0.734	1.119	0.363	0.734	1.119	0.363	0.734	1.119
c_1	30.3	48.6	4.8	26.8	60.1	0.82	19.0	52.0	0.76	12.8	25.2
S	Values of j_1.										
0.2											
.4											
.6		2.77			2.91						
.8	2.85	2.55		3.15	2.60		3.93	2.81		4.68	3.63
1.0	2.65	2.43		2.88	2.44		3.43	2.57		3.92	3.21
1.2	2.53	2.36	3.94	2.72	2.34		3.22	2.44	7.65	3.54	2.98
1.4	2.45	2.31	3.67	2.61	2.27		3.00	2.35	6.57	3.31	2.83
1.6	2.38	2.27	3.48	2.63	2.22		2.88	2.27	5.93	3.15	2.75
1.8	2.34	2.24	3.35	2.48	2.18	5.34	2.79	2.23	5.50	3.04	2.64
2.0	2.30	2.21	3.25	2.43	2.15	5.10	2.72	2.19	5.20	2.95	2.58
2.2	2.27	2.19	3.16	2.39	2.12	4.92	2.66	2.15	4.96	2.88	2.53
2.4	2.24	2.17	3.10	2.36	2.10	4.77	2.61	2.12	4.77	2.82	2.49
2.6	2.22	2.16	3.04	2.34		4.65	2.57	2.10	4.63	2.76	2.45
2.8			2.99			4.55	2.54		4.49	2.72	
3.0			2.94			4.45				2.69	
3.2						4.38				2.66	
3.4						4.32					

The greatest contrast between the rates of variation of the two exponents is found when relations to slope are considered, the least when relations to fineness are considered.

The variations of the two exponents with respect to slope are illustrated by figure 35. In the example from which the curves in this figure were computed the range of variation, within the experimental limits, is considerably above the average, but the example is otherwise typical. The rate of change is everywhere smaller for j_1 than for i_1, and the total change, or range of variation, is therefore smaller. This relation prevails throughout the range of slopes covered by the experiments but would not be found to hold for slopes far outside of that range. The average range of j_1, for the investigated cases, falls between one-half and one-third of the average range of i_1.

It thus appears that a modification of the plan of formulation which dispenses with variation in the coefficient and thereby concentrates all expression of variation in the other parameter, the exponent, tends also to diminish diversity in that parameter.

EFFECT OF CHANGING THE UNIT OF SLOPE.

The values of j_1 are functions not only of the conditions of experimentation and of the constant slope σ but also of the unit used for the measurement of slope. (See p. 99.) In the term log $(1-\sigma)$, which enters into the value of j_1 (equation 42), 1 is the unit of slope; and the relative magnitude of 1 and σ changes as the unit changes. Other terms of the formula are also (implicitly) functions of the unit, but the various influences are not compensatory, and the resultant is of such nature that the values of j_1 vary inversely with the magnitude of the unit. It will be recalled that in the notation of this paper the symbol S pertains to the unit $\frac{\text{height}}{\text{distance}} \div 100$, and the symbol s to the unit $\frac{\text{height}}{\text{distance}}$. The curve marked j_1 in figure 35 represents values of the exponent computed with use of the smaller unit, and the curve marked k represents a coordinate system of values computed with use of the larger unit. The latter curve, produced, would intersect the curve of i_1 at a point corresponding to $s=1$ or $S=100$.

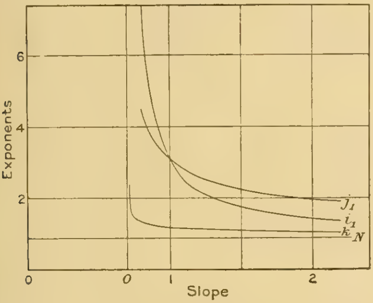

FIGURE 35.—Variations of exponents i_1, j_1, and k, in relation to slope. The scale of slope is in per cent.

It would be possible, by employing the larger unit in the notation for slope, to construct a table equivalent to Table 16 in which the values of j_1 would all be smaller and would have in each series less range. For many of the series they would approach closely the associated values of n. This reduction of exponents would be accompanied by an enormous increase in the values of coefficients, each value of c_1 in the table being magnified by the factor 100^n. The increase would result from the fact that c_1 is the capacity corresponding to unit slope, while the unit slope in that case would be 45°. Considered as capacities, the values of c_1 would be in a sense fictitious, because the laws of traction with which we are dealing do not apply (see p. 63) to so high a slope as 45°.

To recur for a moment to the general account of the index of relative variation, it will be recalled that the index was shown to be independent of the units of the observational quantities. In this particular instance the value of the index, $n\frac{S}{S-\sigma}$, has two factors, of which the first is an abstract number and the second is a ratio between slopes and is independent of the unit of slope. The ordinates of the curve marked i_1 in figure 35 are therefore independent of the slope unit, and the curve is a fact of observation, plus the assumptions of the formula of adjustment.

PRECISION.

Because the values of i_1 were computed from values of n and σ, their precisions are involved with those of n and σ, but the relation is not simple. The precision of n depends partly on the harmony of the observations of load and slope and partly on the precision of σ. It is not feasible to measure the precision of σ for individual series of observations, and the precisions of individual values of n and i_1 are therefore indeterminate. All that has been attempted is to derive a rough estimate of average precision from average values of the quantities involved. The estimated average probable error of values of n is 3.9 per cent, and the corresponding estimate for values of i_1 is 4.6 per cent.

The precision of i_1 varies with slope within each series represented by a column in Table 15, being relatively high for the steeper slopes. The probable error, if measured in the same unit with i_1, is much larger for gentle slopes than for steep; if measured in percentage, it is somewhat larger for the gentler slopes. Measured in percentage, its value for the steeper slopes approximates the corresponding probable error of n.

EVIDENCE FROM EXPERIMENTS WITH MIXED DÉBRIS.

The observations on capacity and slope when the débris transported consisted of a mixture of two or more grades were reduced in the same general manner as those for single grades. It was not thought advisable to make any adjustment of the values of σ, but each logarithmic plot was treated independently. For about one-third of the mixtures the best value appeared to be zero. For another it fell between the values which had been assigned to the finer and coarser components of the mixture. For the remaining third it exceeded the values associated with the components. When the load was a mixture of many grades combined in approximately natural proportions, and also when it consisted of unsorted débris from a river bed, the values of σ were small and for the most part zero.

These features were scrutinized with special interest because the properties of grade (E) had suggested that great range of fineness might determine very low values of σ. On the whole, the data from mixtures favor that view, but their support is by no means unanimous.

TABLE 17.—*Values of i_1 for mixtures of two or more grades of débris.*

Conditions of experimentation: Grade	(A_1C_1)	(A_3G_1)	(A_2G_1)	(A_1G_1)	(A_1G_2)	(A_1G_4)	(B_4F_1)	(B_2F_1)	(B_1F_1)	(B_1F_2)	(B_1F_4)	(C_4E_1)
w	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Q	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363
Parameters of interpolation equation: σ	0.25	0.30	0.20	0	0	0	0.25	0.25	0.50	0.50	0.50	0.30
n	1.06	1.38	1.53	1.98	2.09	2.21	1.08	0.96	1.51	1.59	1.60	1.10
S	Values of i_1.											
0.4												
.6	1.82	2.76	2.30	1.98			1.85	1.64				2.20
.8	1.55	2.21	2.05	1.98			1.57	1.39	4.02	4.23	4.27	1.76
1.0	1.42	1.97	1.92	1.98	2.09	2.21	1.44	1.28	3.02	3.17	3.20	1.57
1.2	1.34	1.84	1.84	1.98	2.09	2.21	1.36	1.21	2.59	2.72	2.75	1.47
1.4	1.30	1.76	1.79	1.98	2.09	2.21	1.31	1.17	2.35	2.47	2.49	1.40
1.6	1.26	1.70		1.98	2.09	2.21		1.14	2.19	2.31	2.33	1.36
1.8						2.21			2.09			1.32
2.0						2.21						

Conditions of experimentation: Grade	(C_2E_1)	(C_2E_1)	(C_1E_1)	(C_1E_1)	(C_1E_2)	(C_1E_2)	(C_1E_4)	(C_1E_4)	(C_4G_1)	(C_2G_1)	(C_1G_1)
w	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Q	0.182	0.363	0.182	0.363	0.182	0.363	0.182	0.363	0.363	0.363	0.363
Parameters of interpolation equation: σ	0	0.30	0	0.40	0.20	0.30	0	0.30	0	0.30	0.50
n	1.78	1.13	1.60	1.12	1.40	1.25	1.55	1.33	1.97	1.24	1.13
S	Values of i_1.										
0.4											
.6		2.26							1.97	2.49	
.8		1.81		2.23		2.02	1.55		1.97	1.99	3.01
1.0		1.62	1.60	1.86	1.75	1.79	1.55	1.90	1.97	1.78	2.26
1.2		1.51	1.60	1.68	1.68	1.67	1.55	1.77	1.97	1.66	1.93
1.4		1.44	1.60	1.56	1.63	1.60	1.55	1.69	1.97	1.58	1.76
1.6	1.78	1.39	1.60	1.49	1.60	1.54	1.55	1.63	1.97	1.53	1.64
1.8	1.78	1.36	1.60	1.44	1.57	1.51	1.55	1.59	1.97	1.49	1.56
2.0	1.78		1.60	1.40	1.55	1.48	1.55	1.56			
2.2	1.78		1.60		1.54	1.45	1.55				

Conditions of experimentation: Grade	(C_1G_2)	(E_4G_1)	(E_2G_1)	(E_1G_1)	(E_1G_2)	$(A_1C_1G_2)$	(CDEFG)			Natural.	
w	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Q	0.363	0.363	0.363	0.363	0.363	0.363	1.82	0.363	0.545	0.182	0.363
Parameters of interpolation equation: σ	0.60	0	0.30	0.40	0	0.48	0	0	0	0.30	0
n	1.47	1.87	1.90	1.28	2.03	1.67	1.63	1.48	1.22	1.43	1.84
S	Values of i_1.										
0.4											1.84
.6		1.87							1.22		1.84
.8		1.87	3.04	2.56		4.19	1.63	1.48	1.22	2.29	1.84
1.0	3.68	1.87	2.71	2.13	2.03	3.22	1.63	1.48	1.22	2.04	1.84
1.2	2.94	1.87	2.53	1.92	2.03	2.79	1.63	1.48	1.22	1.90	1.84
1.4	2.58	1.87	2.42	1.79	2.03	2.55	1.63	1.48	1.22	1.82	1.84
1.6	2.36	1.87	2.34	1.70	2.03	2.39	1.63	1.48	1.22	1.76	1.84
1.8	2.21	1.87		1.64	2.03	2.28	1.63	1.48	1.22	1.72	
2.0					2.03					1.68	
2.4										1.65	
2.6										1.63	
2.8										1.62	

The adjusted values of capacity may be found in Table 12, together with a variety of other data. The values of i_1 are contained in Table 17, having been computed for the range of slopes covered by the observations. In order to compare these with the indexes of relative variation for the single grades from which the mixtures were made, Table 18 has been prepared, containing indexes corresponding to the uniform slope of 1.2 per cent. An analysis of this table shows that 3 mixtures are more sensitive to variation of slope than are components, 13 are less sensitive, and 18 show sensitiveness of intermediate rank. A general average shows the mixtures 11 per cent less sensitive than the (means of) components, but the contrast is much more pronounced for natural river débris and for the most complex artificial combination than for the simpler mixtures.

TABLE 18.—*Comparison of values of i_1 for mixtures and their components.*

[$S=1.2$; $w=1.00$.]

Component grades.		Q	Value of i_1 when ratio of finer to coarser is—						
Finer.	Coarser.		1 : 0	4 : 1	2 : 1	1 : 1	1 : 2	1 : 4	0 : 1
(A)	(C)	0.363	1.81			1.34			1.55
(A)	(G)	.363	1.81	1.84	1.84	[a] 1.98	[a] 2.09	[a] 2.21	3.57
(B)	(F)	.363	1.65	1.36	1.21	2.59	2.72	2.75	2.54
(C)	(E)	.182	1.81		[a] 1.78	[a] 1.60	1.68	[a] 1.55	1.85
(C)	(E)	.363	1.55	1.47	1.51	1.68	1.67	1.77	1.79
(C)	(G)	.363	1.55	[a] 1.97	1.66	1.93	2.94		3.57
(E)	(G)	.363	1.79	[a] 1.87	2.53	1.92	[a] 2.03		3.57
(A), (C)	(G)	.363	1.34			2.79			3.57
Mixture of (C), (D), (E), (F), and (G)		.182	1.81			[a] 1.63			
		.363	1.55			[a] 1.48			3.57
		.545	1.44			[a] 1.22			
Natural combination ranging in fineness from (A) to (F)		.182	2.02			1.90			3.65
		.363	1.81			[a] 1.84			2.54

[a] For these, $\sigma=0$ and $i_1=n$.

The general tenor of the evidence from mixtures is to show that in passing from the laboratory conditions (with graded débris) to natural conditions it will be proper to reduce the estimates of the sensitiveness of capacity to changes of slope.

RELATION OF INDEX TO MODE OF TRACTION.

One of the possible ways of bridging the chasm between laboratory conditions and river conditions is through the consideration of modes of traction. River discharges are enormously greater than the experimental, river slopes are relatively minute, and river channel sections are very dissimilar in form and proportions, but the three modes of traction have the same sequence in rivers as in the laboratory troughs. This consideration has led to the separation of certain data connected with a single mode of traction—the one characterized by smooth surfaces of water and débris. Table 19 contains values of the index of relative variation, i_1, associated with smooth traction and grouped with reference to various conditions. In the upper division of the table all the values pertain to the same grade of débris (C) and are arranged according to discharges and channel widths; in the lower division all pertain to the same width of channel and are arranged according to discharges and grades of débris.

TABLE 19.—*Values of i_1 associated with the smooth mode of traction.*

I. Values pertaining to the same grade of débris, (C).

Width (feet).	Value of i_1 for discharge (ft.³/sec.) of					
	0.093	0.182	0.363	0.545	0.734	1.119
0.44	2.15	1.88				
.66	1.79	1.70	1.59	1.59	1.58	
1.00		1.81	1.59	1.48	1.48	
1.32		2.20	1.61	1.55	1.51	
1.96			1.96	1.79	1.62	1.93

II. Values pertaining to the same width of channel, 0.66 feet.

Grade.	Value of i_1 for discharge (ft.³/sec.) of –					
	0.093	0.182	0.363	0.545	0.734	1.119
(B)	2.09	1.82	1.61	1.54		
(C)	1.79	1.70	1.59	1.59	1.58	
(D)	2.01	1.72		1.64		
(E)		1.99	2.13			
(G)			2.41		2.19	2.20
(H)			3.35		2.65	2.54

Inspection of the table shows that under this special condition the index (1) varies inversely with discharge, (2) varies inversely with fineness, and (3) varies both inversely and directly with width. In all these respects the variations are similar to those noted when the constant condition is slope, but the rates of variation are not the same. To illustrate the differences in rate I introduce Table 20, in which data of Table 19 are compared, in parallel columns, with similar data (from Table 15) conditioned by constant slope. The same data are also presented graphically and with some generalization in figure 36. On giving attention to the first division of the table and to the upper diagram, it will be seen that the variation of the index with discharge is somewhat less when the constant factor is mode of traction than when it is slope. The second division and second diagram show that the variation with fineness is also less for constant mode of traction. The third division and diagram indicate that the variation with width of channel is of the same order of magnitude in the two cases, but that for constant mode of traction the minimum value of the index is associated with greater width.

The comparison does not indicate that the condition of uniform mode of traction is greatly to be preferred to that of uniform slope as a basis for the extension of laboratory generalizations to large natural streams.

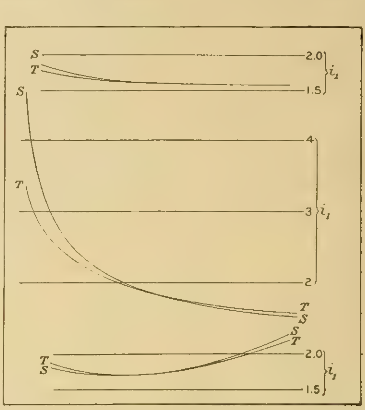

FIGURE 36.—Variations of i_1 under condition of uniform mode of traction (*T*, *T*, *T*), and under condition of uniform slope (*S*, *S*, *S*). Vertical distances represent i_1, with a common scale but different zeros. Horizontal distances represent, for the upper pair of curves, discharge; for the second pair, logarithms of fineness; for the lower pair, width of channel; the values increasing from left to right.

TABLE 20.—*Relations of i_1 to discharge, débris grade, and channel width, when conditioned (1) by a constant mode of traction and (2) by a constant slope.*

Grade, (C) *w*, 0.66 foot.			*w*, 0.66 foot. *Q*, 0.363 ft.³/sec.			*Grade*, (C) *Q*, 0.182 ft.³/sec.		
Q	Values of i_1 with—		Grade.	Values of i_1 with—		*w*	Values of i_1 with—	
	Smooth traction.	Constant slope 1.0 per cent.		Smooth traction.	Constant slope 1.4 per cent.		Smooth traction.	Constant slope 1.2 per cent.
0.093	1.79	1.87	(B)	1.61	1.54	0.44	1.88	1.81
.182	1.70	1.73	(C)	1.59	1.55	.66	1.70	1.70
.363	1.59	1.59	(E)	2.13	1.99	1.00	1.81	1.81
.545	1.59	1.58	(G)	2.41	2.71	1.32	2.20	2.27
.734	1.58	1.57	(H)	3.35	4.69	....	....	....

IN CHANNELS OF SIMILAR SECTION.

THE CONDITIONS.

It will be shown in the following chapter that one of the important conditions affecting capacity is the relation of stream depth to stream width, or the form ratio *R*. The matter has, in fact, already received some attention in connection with the variation of σ. Now, in each observational series the width is constant while the depth varies, so that the form ratio is a variable. Its variations accompany and are inseparable from those of slope; and the variation of capacity (within an observational series), which up to this point has been treated as if it were purely a function of slope, is in reality a function of slope and form ratio jointly. To separate the two factors and thereby discover the relation of capacity to slope for streams of similar section, it is necessary to bring together data obtained by use of troughs with different widths, selecting points of two or more adjusted series which are characterized by the same ratio of depth to width. In every such comparison the capacity and slope associated with the narrower trough are relatively large, while for the wider trough they are relatively small. The opportunities for comparison are not abundant, because in the main the observational series which are of like conditions except as to width do not overlap in respect to form ratio.

SIGMA AND THE INDEX.

In the records of the main body of experiments 24 cases of overlap are found, all associated with the finer grades of débris, from (A) to (D). In each of these the comparison includes two widths only, no instance occurring in which it can be extended to three. There is, however, a special group of experimental series, planned in part for this particular purpose, in which the trough-width interval is so small that triple overlaps occur. The special experiments were made with débris of grade (C); the trough widths were 1.0, 1.2, 1.4, 1.6, 1.8, and 1.96 feet; and the experiments yield nine triple overlaps. In six of these the extent of overlap is such that numerical comparisons have been made for more than one value of R.

With the aid of the computation sheets described on page 95, a table was compiled in which adjusted capacities and slopes were arranged with respect to form ratio, and in this table, which has not been printed, the matter of overlaps was canvassed. Table 21 contains the data involved in the triple overlaps.

TABLE 21.—*Selected data, for grade (C), showing the relation of capacity to slope when the form ratio is constant.*

R	$Q=0.734$			$Q=0.923$			$Q=1.021$			$Q=1.119$		
	w	S	C	w	S	C	w	S	C	w	S	C
0.07	1.60	1.38	354									
	1.80	1.17	262									
	1.96	.75	118									
.08	1.60	1.08	226									
	1.80	.89	151									
	1.96	.49	48									
.09				1.60	1.29	413						
				1.80	.94	210						
				1.96	.58	88						
.10	1.40	1.33	346				1.60	1.19	405			
	1.60	.72	102				1.80	.82	195			
	1.80	.55	57				1.96	.50	75			
.11	1.40	1.06	224	1.40	1.44	522				1.60	1.07	380
	1.60	.60	71	1.60	.83	185				1.80	.74	193
	1.80	.45	35	1.80	.60	83				1.96	.50	88
.12				1.40	1.17	357				1.60	.87	261
				1.60	.69	130				1.80	.62	134
				1.80	.50	56				1.96	.41	55
.13	1.20	1.43	382	1.40	.96	243	1.40	1.16	380			
	1.40	.72	103	1.60	.58	94	1.60	.65	135			
	1.60	.44	37	1.80	.42	36	1.80	.47	58			
.14										1.40	1.20	470
										1.60	.60	130
										1.80	.45	66
.15										1.40	.99	331
										1.60	.51	95
										1.80	.39	47
.16										1.40	.83	236
										1.60	.44	71
										1.80	.34	33

To illustrate the use made of such data, the case of $Q=1.119$ ft.³/sec. and $R=0.15$ is selected. In that example the values of slope and capacity are given for the trough widths 1.4, 1.6, and 1.8 feet. These values come from three adjusting equations, which are, for the widths severally, $C=386\ (S-0.08)^{1.72}$, $C=400\ (S-0.10)^{1.60}$, and $C=430\ (S-0.12)^{1.67}$. The graphs of the equations are shown in figure 37. On each graph is a dot indicating the point which corresponds to the tabulated values of C and S, and for each of these points the ratio R is 0.15. The curves represent the relations of C to S under the condition of uniform width. The three dots are points on an undrawn curve to express the relation of C to S under the condition of constant form ratio.

It is convenient, in discussing this undrawn curve, to assume that its equation involves σ and is otherwise of the same type as the equations used in discussing the data for constant width. In this case, moreover, the assumption is countenanced by the fact that traction is limited by the competent slope. By making the assumption, it is possible to compute all the parameters of the curve from the coordinates of the three known points and write its equation:

$$C = 469\ (S - 0.23)^{1.25} \qquad \ldots\ldots(43)$$

In the present connection the most significant of the parameters is σ; and the values of σ have been computed for each of the cases of Table 21. They are assembled in Table 22.

TABLE 22.—*Values of σ corresponding to data in Table 21.*

R	Value of σ when Q is—			
	0.734	0.923	1.021	1.119
0.07	0			
.08	0			
.09		−.44	+.04	
.10	+.20			
.11	+.20	+.35		+.05
.12		+.33		+.11
.13	+.14	+.31	+.13	
.14				+.21
.15				+.24
.16				+.24

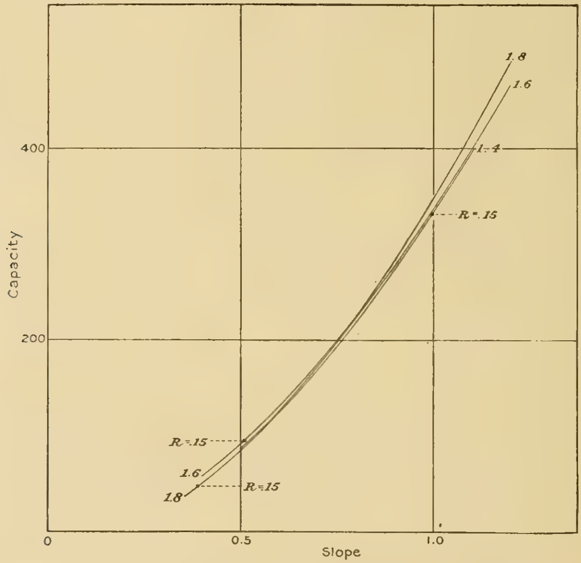

FIGURE 37. Curves of $C = f(S)$ for trough widths of 1.4, 1.6, and 1.8 feet, showing points which agree as to form ratio. Grade (C). $Q = 1.119$ ft.³/sec. $R = 0.15$.

One value of σ has a negative sign. As this yields positive capacity for negative slope, thus transcending the physical conditions of traction, and as the value is numerically large, an error of importance is betrayed. The error appears not to be one of computation and must be ascribed either to the observational data or to assumptions made in the work of reduction and adjustment. In either case its existence serves to qualify the values of σ as of low precision.

In view of that qualification, the study of the values of σ in detail appears unprofitable and only their mean will be considered. In deriving the general mean a subsidiary mean was first found for each case of overlap and these were afterward combined, this course being followed because when several values of σ are derived from the same overlap of series they are not independent. The general mean thus derived is +0.08, and this may be compared with a mean similarly obtained from the associated equations under condition of constant width, namely, +0.12. So far as this moderate difference in magnitude has significance, it indicates that the index of relative variation, i_1, has the smaller range under the condition of constant form ratio; for the index's range in magnitude is a direct function of σ.

THE SYNTHETIC INDEX.

Another mode of viewing the data of Table 21 ignores the middle term of the triple overlap and considers only the first and last. From the values of capacity and slope in these two terms a value of the synthetic index can be computed by equation (35). It is possible in this way to broaden the range of data by including the cases of simple overlap; and it is possible to make many pertinent comparisons by computing the corresponding values of the synthetic index for observational series in which the constant condition is width instead of form ratio. The indexes with form ratio constant and with width constant may be symbolized severally by I_R and I_w.

Table 23.—*Values of synthetic index under condition that R is constant, (I_R); with coordinate values, under condition that w is constant, (I_w).*

Grade.	Q.	Width.		R.	I_R.	I_w.	
						Channel narrow.	Channel wide.
(A)	0.363	1.32	1.96	.06	2.01	1.74	1.99
				.07	2.23	1.80	2.17
	.734	1.32	1.96	.10	1.77	1.82	1.75
				.12	1.90	....	....
(B)	.182	1.00	1.32	.06	1.95	1.87	1.92
				.07	2.09	2.00	2.02
				.08	2.22	2.06	2.16
				.09	2.49	....	....
	.363	.66	1.00	.20	1.69	....	1.75
	.545	1.32	1.96	.07	2.00	1.75	1.96
				.08	2.11	....	....
	.734	1.00	1.32	.20	1.80	1.69	1.82
	.734	1.32	1.96	.12	2.05	....	....
(C)	.182	.44	.66	.30	1.71	....	1.88
	.182	.66	1.00	.10	1.74	1.69	1.79
				.12	1.88	1.75	1.92
				.14	2.02	1.82	2.04
	.182	1.00	1.32	.05	2.11	1.70	....
				.06	2.36	1.77	2.26
				.07	2.67	1.87	2.43
	.363	.66	1.00	.20	1.53	1.62	1.64
				.30	1.96	....	2.07
		1.00	1.32	.10	1.72	1.58	1.66
				.12	1.87	1.65	1.88
	.363	1.32	1.96	.06	2.22	1.72	2.24
	.545	1.00	1.32	.12	1.56	1.44	1.52
				.14	1.64	1.48	....
	.734	.66	1.00	.40	1.46	1.20	1.60
	.734	1.00	1.32	.16	1.47	1.48	....
				.18	1.54	1.52	....
				.20	1.59	1.73	....
	.734	1.20	1.60	.13	2.01	1.91	....
	.734	1.32	1.96	.09	1.60	....	....
	.734	1.40	1.80	.10	2.06	2.00	2.01
				.11	2.17	....	....
	.734	1.60	1.96	.07	1.81	1.92	1.95
				.08	1.96	1.98	2.07
	.923	1.40	1.80	.11	2.10	....	....
				.12	2.18	1.91	2.08
				.13	2.30	....	....
	.923	1.60	1.96	.09	1.93	1.86	1.98
	1.021	1.40	1.80	.13	2.08	1.99	....
	1.021	1.60	1.96	.10	1.95	1.86	1.99
	1.119	1.40	1.80	.14	2.00	....	....
				.15	2.10	1.49	2.13
				.16	2.20	....	....
	1.119	1.60	1.96	.11	1.93	1.87	2.07
				.12	2.07	1.94	2.13
(D)	.363	1.00	1.32	.10	2.02	1.67	....
	.734	1.00	1.32	.16	1.86	....	....
				.18	1.94	1.66	....
				.20	2.11	1.72	1.97
Adjusted means					1.88	1.72	1.89

Table 23 contains values of I_R computed for the 9 cases of overlap shown in Table 21 and for 24 cases of simple overlap previously mentioned. Where the overlap is extensive, values of I_R were computed for two or more values of R. Each of these values is based on data of two width-constant series, pertaining to different trough widths, and whenever the extent of such an associated width-constant series permitted, a value of I_w was computed from its data for the same range of slope as that covered by the value of I_R. The table thus comprises data for the coordinate values of the indexes under conditions of constant form ratio and constant width.

The most important generalization from the data in Table 23 is contained in the adjusted means which appear at the bottom. In the derivation of these means due account was taken of the fact that the several individual values from the same overlap are not independent and also of the fact that the coordinate data for constant width are incomplete. The mean for constant form ratio, 1.88, is practically the same as that one for constant width which is associated with the wider channels, 1.89, and is notably greater than the mean associated with the narrower channels, 1.72. On the whole it is indicated that the sensitiveness of capacity to slope is the greater for traction conditioned by constant form ratio, in the proportion of 1.88 to 1.805, or as 1.04 to 1.

When the values of I_R and I_w are arranged according to the associated values of R, the following relations are brought out:

R	Mean I_R.	Mean I_w.		$\frac{I_R}{I_w}$
		Narrower trough.	Wider trough.	
0.05 to 0.08	2.14	1.86	2.10	1.08
.09 to .12	1.93	1.81	1.94	1.03
.14 to .40	1.80	1.63	1.86	1.03

SUMMARY.

Only a small fraction of the observational data are available for the discussion of the capacity-slope relation under the condition of constant form ratio, and the discussion is therefore limited to a comparison of its features under that condition with corresponding features under the condition of constant channel width. The results of such comparison may be summarized as follows: The sensitiveness of tractional capacity to variation of slope is in general greater under the condition of constant form ratio, but the difference is of moderate amount. The difference is somewhat less (at least within the limits of available data) for broad and shallow streams than for streams that are narrow and deep. The range of sensitiveness, or its variation with variation of slope, appears to be somewhat less under the condition of constant form ratio. The generalizations in regard to traction by currents of variable depth but invariable width may be extended, with only moderate qualification, to the case of currents which retain geometric similarity of section while slope is varied.

REVIEW.

With increase of the slope of descent goes increase of a stream's energy (per unit time, per unit distance). With the increase of energy goes increase of capacity for the transportation of débris along the channel bed. The increase of energy is strictly proportional to the increase of slope, but the increase of capacity follows a different law. The law is not simple, but one feature persists through all its manifestations: The capacity for traction increases more rapidly than the slope. The difference in rapidity, or the magnitude of the difference between the rates of change for capacity and slope, is itself a variable, depending on a variety of conditions. The study of the relation of capacity to slope is here treated as a study of the influence of conditions on the magnitude of the difference between the two rates of change.

The magnitude of that difference is indicated by a quantity, of the nature of an exponent, called the index of relative variation (of capacity, as compared to slope), and designated by i_1. The index may be defined as the first differential coefficient of log C with respect to log S. It is illustrated by saying that the capacity varies, instantaneously, as the i_1 power of the slope.

For the greater part of the field covered by the experiments the index falls between 1.4 and 3.0, but under some conditions it is considerably higher. It varies with slope, being higher for low slopes and lower for high. It varies with discharge, being relatively high for small discharges. It varies with fineness, being relatively high for coarse débris. Briefly, it varies inversely with slope, discharge, and fineness. It varies also with width of channel, decreasingly for relatively narrow channels and increasingly for relatively broad channels; so that, for any particular combination of slope, discharge, and fineness there is a width characterized by a minimum value of the index.

It is furthermore true that no one of these variations is itself constant in rate, the rate of each having its own law of variation. Thus the complexity of the relation of capacity to slope is such as to be characterized by variations of the rates of variation of rates of variation; and there are even vistas of higher orders of variability. The law connecting capacity with slope may be susceptible of much more compact expression, but such formulation must probably await the development of a mechanical theory of stream traction.

Formulation founded on the index of relative variation, while bringing out clearly certain general features of the law, is not able to afford a complete quantitative statement. It may be likened to a map in definite hachures as contrasted with one in definite contours. As the hachure tells the direction and rate of slope but omits the absolute altitude, so the index tells the relative change under given conditions but omits the absolute capacity. To remedy this defect, the experiment was tried of substituting for the equation $C=v_1S^{i_1}$, in which v_1 is variable, the equation $C=c_1S^{j_1}$, in which c_1 is constant for each series of observations. Formulation by means of c_1 and j_1 is more nearly analogous to the contour map, but the variability of the exponent j_1 is no less formidable than that of i_1 while the definition and derivation of j_1 are less simple and its significance is less clear.

Further utilizing the analogy of the map, we may think of the capacity-slope relation as an undulating topography, in which the vertical element is $\frac{C}{S}$ or $\frac{f(C)}{f_1(S)}$ and the horizontal elements are qualifying conditions. Formulation is a mode of representing this topography, the hills and valleys of which do not depend on the mode but are real. Two modes have been tried, each with limitations, but the ideal mode is not known. The contour map or the relief model would serve admirably if the qualifying conditions were two only, but as they number at least four, a graphic or plastic expression is possible only in space of n dimensions.

By reason of the complexity of the relation of capacity to slope and because of the lack of a mechanical theory of flow and traction, the laboratory data do not warrant inferences as to the quantitative relations of capacity to slope for rivers.

Of various attempts to evade the complexity, two are thought worthy of record. In each series of experiments the mode of traction changes with increase of slope, first from dune to smooth, then from smooth to antidune, but the critical slopes are not the same for different discharges or widths or degrees of fineness. It appeared possible to gain in simplicity by treating separately the data associated with a single mode of traction, and data for the smooth mode were accordingly segregated and discussed. Greater simplicity was not found, but the range of variation is somewhat smaller for the single mode of traction.

The second attempt was connected with the form of cross section of the current. Within a single series of experiments the width was constant and the depth varied, so that the capacity was conditioned not only by slope but by form ratio, $R=\frac{d}{w}$. By comparing one observational series with another it is possible to obtain data conditioned by difference in slope, but without difference in form ratio. The discussion of such data developed only moderate modification of the results previously obtained and no reduction in complexity.

DUTY AND EFFICIENCY.

For the purposes of this paper duty has been defined as the ratio of capacity to discharge: $U=\frac{C}{Q}$. Combining this with $C=f(S)$, the most general expression for the relation of capacity to slope, we have $U=\frac{f(S)}{Q}$. Under no form discovered for $f(S)$ is this expression reducible to simpler terms. For each value of discharge, duty is simply proportional to capacity; and the entire discussion of this chapter applies to duty as well as capacity. The parameters, n, i_1, j_1, I_w, and σ may be transferred, without modification, to formulas for duty.

Efficiency has been defined as the ratio of capacity to the product of discharge by slope:

$$E=\frac{C}{QS} \quad \text{(44)}$$

The combination of this with

$$C=v_1S^{i_1} \quad \text{(36)}$$

yields

$$E=v_1\frac{S^{i_1}}{QS}=\frac{v_1}{Q}S^{i_1-1} \quad \text{(45)}$$

The transformation of the exponent is important. While capacity varies as the i_1 power of slope, efficiency varies as the i_1-1 power. The index of relative variation is 1 less for efficiency than for capacity. Table 15 could therefore be adapted to efficiency by diminishing all its values by unity. As the lowest known values of i_1 are greater than unity—the lowest in Table 15 is 1.31—it follows that efficiency is an increasing function of slope under all tested conditions.

The combination of (44) with

$$C=e_1S^{i_1}\text{-------------}(40)$$

yields

$$E=\frac{e_1}{Q}S^{i_1-1}\text{-------------}(46)$$

showing that in passing from the field of capacity to that of efficiency the exponent associated with a constant coefficient also is reduced by unity.

Following the form of equation (35), we have

$$I_1=\frac{\log C''-\log C'}{\log S''-\log S'}\text{---------}(35a)$$

where C' and C'' are specific values of capacity corresponding severally to the slopes S' and S''. Designating by I_e the synthetic index of efficiency in relation to slope, and by E' and E'' the efficiencies corresponding to C' and C'', we have

$$I_e=\frac{\log E''-\log E'}{\log S''-\log S'}\text{-----}(35b)$$

As $C=ESQ$, $\log C'=\log E'+\log S'+\log Q$, and $\log C''=\log E''+\log S''+\log Q$. Substituting these values in (35a) and reducing, we have

$$I_1=\frac{\log E''-\log E'}{\log S''-\log S'}+1$$

Subtracting the members of this expression from those of (35b) and transposing, we have

$$I_e=I_1-1\text{-------}(47)$$

That is, the synthetic index of relative variation of efficiency with reference to slope is less by unity than the corresponding index for capacity.

It is evident that at competent slope, when capacity is zero, efficiency also is zero. Like capacity, it increases with increase of slope. Under the assumption that its law of increase is of the same type, its value varying with a power of $(S-\sigma)$, two expressions have been derived, but neither has been found reducible to simple form. The algebraic work being omitted, they are

$$E=v_{\text{II}}(S-\sigma)^{n-\frac{S-\sigma}{S}}$$

$$E=\frac{b_1}{Q}(S-\sigma)^{n-\frac{\log S-2}{\log(S-\sigma)-2}}$$

In the first of these expressions the coefficient is variable, being a function of S; so that the exponent may be regarded as the index of relative variation for efficiency in relation to $(S-\sigma)$. As $\frac{S-\sigma}{S}$ falls to zero when S falls to the limiting value σ, and as it approximates unity when S is indefinitely large, the values of the exponent lie between n and $n-1$ for all practical cases. In the second expression the coefficient is constant, with respect to slope, but the exponent is transcendental and intractable.

Thus it appears that the derived expression for efficiency as a function of $S-\sigma$ is not simply related to the coordinate expression for capacity and is not available for practical purposes; but it does not necessarily follow that the actual relation of efficiency to slope can not be formulated for practical purposes by an equation of the sigma type. All that is really shown is that if capacity and efficiency are both formulated in that way, the results are not consistent. Formula (10) was adopted for the capacity-slope relation, not because it expresses a demonstrated law of relation, but because it so far simulates the real law of relation as to be available for the marshaling of the observational data. It seems quite possible that had the data been first translated from terms of capacity into terms of efficiency, the type of formula would have been found equally available.

By way of testing the matter a few comparative computations were made, observational series being selected for the purpose from those which in the adjustment gave small probable errors. From the original data in Table 4 values of efficiency were computed, and these were plotted on logarithmic paper in relation to $S-\sigma$, the values of σ being those employed in the adjusting equations. In four of the nine cases treated the locus indicated was a straight line; and the drawing of the line gave values of B and n_{II} in $E=B\ (S-\sigma_1)^{n_{II}}$. In each of the remaining five cases the indicated locus was a curve, and the curvature was such as to indicate a larger constant in place of σ. This larger constant, σ_1, was determined graphically, and the other parameters were computed as before. The results are given in Table 23a, together with comparative data from Table 15.

TABLE 23a.—*Comparison of parameters in the associated functions of capacity and efficiency.* $C=b_1(S-\sigma)^n$ *and* $E=B\ (S-\sigma_1)^{n_{II}}$.

Grade.	w	Q	b_1	B	σ	σ_1	$\sigma_1-\sigma$	n	n_{II}	$n-n_{II}$
(B)	0.66	0.182	39.8	196	0.10	0.10	0	1.64	0.67	0.97
(B)	1.00	.363	97.5	268	.08	.18	.10	1.54	.56	.98
(C)	.66	.182	38.6	187	.11	.11	0	1.54	.63	.91
(C)	.66	.545	123	193	.06	.06	0	1.48	.56	.92
(C)	1.00	.363	100	280	.11	.31	.20	1.48	.37	1.11
(C)	1.32	.363	100	240	.16	.22	.06	1.40	.54	.86
(G)	.66	.734	64.5	78	.36	.56	.20	1.69	.74	.91
(G)	1.00	.734	65.7	63	.41	.41	0	1.70	.96	.74
(H)	.66	.734	52.9	58.6	.56	.76	.20	1.72	.80	.92
Means							.09			.92

The proximate inferences from these plots and comparisons are, first, that efficiency may be formulated, with sufficient accuracy for practical purposes, as proportional to a power of $S-\sigma_1$; second, that, when it is thus formulated, the approximate values of σ_1 are in general larger than the values of σ obtained in the formulation of capacity; and, third, that the values of the exponent are smaller than the equivalent values for capacity, the differences usually being somewhat less than unity.

The field of these inferences was also traversed by a mathematical inquiry, of which the results are more definite. If the relation of efficiency to slope be formulated by

$$E=B\ (S-\sigma_1)^{n_{II}} \qquad (47a)$$

the exponent n_{II} is always less than n, but never so small as $n-1$. For the range of conditions covered by the experiments, it is little greater than $n-1$. The value of σ_1 is always greater than the corresponding value of σ, the difference being usually small. The difference is greater when the value of the exponent is relatively small. Equation (47a) is incompatible with the corresponding equation for capacity, (10). If the locus of $E=f(S)$ be separately plotted by means of the two equations, the resulting curves are not coincident, but they intersect at three points and lie close together elsewhere (in the practical field) unless the difference between σ and σ_1 is large.

On the whole, it appears entirely feasible to formulate efficiency by means of equation (47a).

CHAPTER IV.—RELATION OF CAPACITY TO FORM RATIO.

INTRODUCTION.

Details of channel form in a natural stream are highly diversified. In connection with the bendings to right and left the current is thrown to one side and the other, with the result that the cross section is not, for the most part, symmetric about a medial axis but shows greater depth on the side of the swifter flow. In the straight channels of the laboratory there was little departure from bilateral symmetry and the cross section was approximately rectangular. For this reason those relations of traction to form of cross section which are found to exist in the laboratory can not, in general, be inferred of natural streams. Nevertheless there is probably an approximate correspondence between the two types when the tractional properties of a broad, shallow channel are compared with those of a narrow, deep channel; and to that extent the discussion of form ratio $(R=\frac{d}{w})$ is pertinent to the problems of natural streams.

In connection with the study of the laboratory data the form ratio is a factor of great importance, for not only is capacity for traction directly conditioned by it, but it affects every law of relation between capacity and another condition.

In the discussion of capacity in relation to slope the effects which might have been referred to form ratio were treated instead as due to width, while small account was taken of the coordinate influence of depth. For many purposes the choice of viewpoint is indifferent, but when large and small channels are to be compared there is decided advantage in taking account of form ratio. The form ratios of laboratory channels and river channels, for example, are of the same order of magnitude, but the widths are not.

SELECTION OF A FORMULA.

MAXIMUM.

When identical discharges are passed through troughs of different width and are loaded with débris of the same grade, and the loads are adjusted so as to establish the same slope, it is usually found, not only that the capacity varies with the width, but that some intermediate width determines a greater capacity than do the extreme widths. That is, the curve of capacity in relation to width exhibits a maximum. The form ratio varies inversely with the width; and the same maximum appears when the capacity is compared with form ratio. The curves in figure 38, introduced to illustrate this fact, show data from Tables 12 and 14 for grade (C), with $Q=0.363$ ft.^{3}/sec. and $S=1.0$ per cent. In the upper curve capacities are compared with widths; in the lower one the same capacities are compared with form ratios.

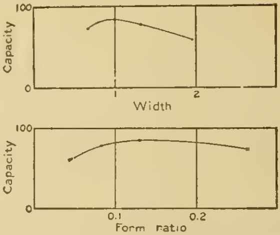

FIGURE 38.—Illustration of the relation of capacity to width of channel and to form ratio, when slope and discharge are constant.

The formula for the discussion of such relations must be one affording a maximum. It must also satisfy various physical conditions, as will presently appear.

The explanation of the maximum, so far as its main elements are concerned, is not difficult. The phenomenon was in fact anticipated in the planning of the experiments, and certain courses of experimentation were arranged with special regard to the discovery of the form ratio of highest efficiency.

Conceive a stream of constant discharge and flowing down a constant slope but of variable width. The field of traction is determined by the width, and the evident tendency of this factor is to make the capacity increase as the width increases. The rate of traction for each unit of width is determined by the bed velocity in that unit, and the bed velocity is intimately associated with the mean velocity. Velocity varies directly with depth, and, inasmuch as increase of width causes (in a stream of constant discharge) decrease of depth, the tendency of this factor is to make capacity decrease as width increases. Velocity is also affected by lateral resistance, the retarding influence of the side walls of the channel. The retardation is greater as the wall surface is greater, therefore as the depth is greater, and therefore as the width is less. As capacity varies inversely with the retardation, and as the retardation varies inversely with width, it follows that the tendency of this factor is to make capacity increase as width increases. Thus the influence of width on capacity is threefold: Its increase (1) enlarges capacity by broadening the field of traction, (2) reduces capacity by reducing depth, and (3) enlarges capacity by reducing the field of side-wall resistance. Now, without inquiring as to the laws which affect the several factors, it is evident that when the width is greatly increased a condition is inevitably reached in which the depth is so small that the velocity is no longer competent and capacity is nil. It is equally evident that when the width is gradually and greatly reduced the field of traction must become so narrow that the capacity is very small, and eventually the current must be so retarded by side-wall friction that its bed velocity is no longer competent and capacity is nil. For all widths between these limits capacity exists, and somewhere between them it attains a maximum.

The forms of algebraic function which afford a maximum are many; but no general examination of them is necessary, because the physical conditions of the problem serve to indicate the appropriate type. As just observed, the variation of form ratio (when discharge and slope are constant) involves simultaneous variations of width and depth. To develop an expression for the relation of capacity to form ratio, it is convenient first to determine separately the relations of capacity to width and to depth, and then to combine the two functions.

CAPACITY AND WIDTH.

To consider separately the response of capacity for traction to variation of width it is necessary to relinquish, for the time being, the assumption of constant discharge and variable depth, and substitute for it the assumption of constant depth and slope, with variable discharge. That is, we are to conceive a stream of constant slope, of which the width is progressively increased or diminished and of which the discharge is varied in such way as to maintain a constant depth. Figure 39 represents the cross section of such a stream, whether natural or of the laboratory type.

Near the sides the current is retarded by side friction. Also, the freedom of its internal movements is restricted by the sides, just as it is everywhere restricted by the upper surface and the bed. These lateral influences diminish with distance from the sides and finally cease to be perceptible. We may thus recognize, in a broad stream, two lateral portions, *AB*, in which capacity is affected by the sides, and a medial portion, *AA*, in which capacity is not thus affected. In the medial portion total capacity is strictly proportional to the distance $\overline{AA}$; or, in other words, the capacity per unit distance, C_1, is uniform. In a lateral portion the capacity per unit distance diminishes as the side is approached. Whatever the law of diminution, the total capacity of a lateral portion is equivalent to the capacity per unit distance in the medial portion, multiplied by some distance $\overline{AD}$, less than $\overline{AB}$. Therefore the total capacity for the whole stream is

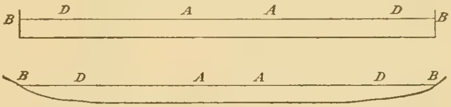

FIGURE 39.—Cross sections of stream channels; to illustrate the relation of capacity to width.

$$C = C_1(\overline{AA} + 2\overline{AD}) = C_1(w - 2\overline{DB}) \ldots\ldots\ldots (48)$$

It is evident that for a shallow stream the distances $\overline{AB}$ and $\overline{DB}$ are less than for a deep stream; and while the assumption may not be strictly accurate, it must be approximately true that $\overline{DB}$ is proportional to the depth. Making that assumption and introducing the numerical constant α, I replace $2\overline{DB}$ by αd, and write

$$C = C_1(w - \alpha d)$$

As we are here concerned only with the law of variation of C, we may conveniently replace this by the proportion

$$C \propto w - \alpha d.$$

Substituting for d its equivalent Rw,

$$C \propto w\,(1-\alpha R).$$

As d is by postulate constant, and as $w=\frac{d}{R}$, $w \propto \frac{1}{R}$. We may therefore substitute $\frac{1}{R}$ for w in the proportion above, obtaining

$$C \propto \frac{1-\alpha R}{R} \text{ ------------ } (49)$$

This expression gives the relation of capacity to form ratio, so far as that relation depends on variation of width. Eventually it is to be complemented by an expression similarly dependent on variation of depth.

The preceding analysis involves the assumption that the stream is so broad, in relation to its depth, that its medial portion is unaffected by lateral influences. The resulting proportion, (49), is not necessarily applicable to narrower streams. It is quite conceivable that when the channel is so narrow that the reaction of the sides affects all parts of the current the variation of capacity follows a different law. The analytic consideration of the case of narrower channels has not been attempted, but some information has been obtained from the experiments. The following examination of experimental data is directed toward this question and also toward that of the magnitude of the constant α.

TABLE 24.—*Relation of capacity for traction to width of channel, when slope and depth are constant.*

Grade.	Slope (per cent).	Depth (feet).	Value of *C* when width (feet) is—					
			0.23	0.44	0.66	1.00	1.32	1.96
(B)	0.8	0.08	....	....	8.4	[17.4]	20.4	43
		.10	....	....	15	26.6	35.4	66
		.12	....	8.6	21.0	38.0	57.5	95
		.15	....	15.2	36.7	60.0	112	145
		.20	2.8	32.0	62.5	113	....	....
	1.2	.08	....	....	29	50	88	142
		.10	....	22.1	46	74	156	211
		.12	....	32.0	65	103	....	290
(C)	.8	.10	....	....	12.5	22.0	25.0	42
		.12	....	....	19.2	34	....	76
		.14	....	[5.3]	27	51	78	135
		.20	....	....	52	111	....	....
	1.2	.10	....	....	45	80	109	171
		.12	....	....	[64]	115	151	[300]
		.14	....	20.0	81	156	221	480
			Geometric means.					
(B) and (C).	0.8 and 1.2	.08	....	....	15.6	29.4	42.4	78.0
		.10	....	....	29.6	50.7	75.2	115
		.12	....	....	36.1	62.5	....	158
		.14 .15	....	11.7	43.1	78.2	124	211

The assumptions of the present section include constant slope and constant depth, with discharge and capacity adjusted to variation of width. The experiments involve constant width and constant discharge, with automatic adjustment of slope and depth to variation of load. In order to check the analysis by means of the laboratory data it is necessary to employ some method of interpolation. Two methods were tried, but only one need be described.

Attention being first restricted to a particular grade of débris and a particular slope of channel, the computation sheets (p. 95) for the different discharges were entered with a particular depth as argument, and the associated values of capacity and slope were taken out. These values were plotted on logarithmic section paper as a series of points. Through these points was drawn a curve—the locus of $\log C=f(\log S)$, under the condition that d is constant. By means of this curve values of C were interpolated, corresponding to selected values of S. The process was then repeated with other depths, other widths, and other grades; and in this way were obtained sets of values of capacity in relation to width, under the condition of constant depth and slope. Such interpolated values of capacity are presented in Table 24. It was found that the data for grades (B) and (C) only are full enough to serve the present purpose.

The tabulated capacities are also plotted, in relation to width, in the upper and second divisions of figure 40. If the data were precise, and if equation (48) were strictly accurate, the oblique lines of the figure would all be straight and would all intersect the line of zero capacity somewhere to the right of the origin. The irregularities of the lines are of such distribution as to indicate that they are occasioned chiefly by the imperfection of the data, and so far as may be judged by their inspection the formula is substantially correct.

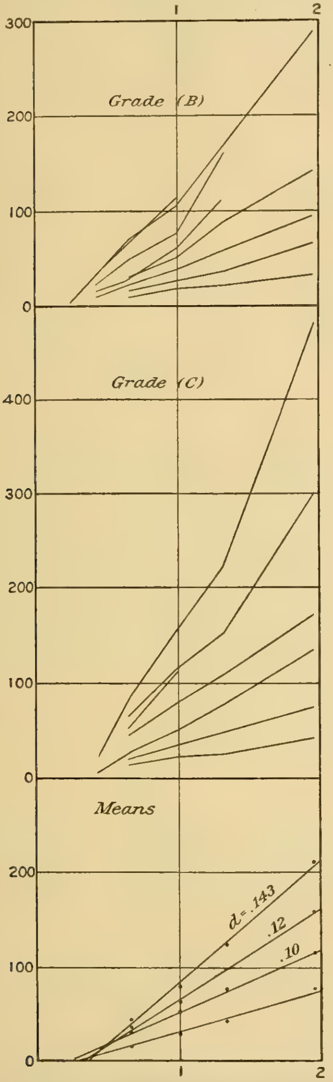

FIGURE 40.—Capacity for traction in relation to width of channel, when depth and slope are constant. Scale of capacities, vertical; widths, horizontal.

As the individual lines do not well indicate the points of intersection with the horizontal axis, a set of composites were prepared, each combining the data for a particular depth, without distinction as to grade of débris or slope of channel. In the computations for these a few interpolations were first made, and then the capacities were combined by taking their geometric means. The numerical results appear at the bottom of Table 24, and these are represented by dots in the lower division of figure 40. The indications of the dots were then generalized by drawing straight lines among them, and the intersections of these lines with the line of zero capacity gave points corresponding to D in figure 39. More strictly, the distance of each intersection from the origin gave an estimate of the quantity $2\,\overline{DB}$ in equation (48). As each estimate is associated with a particular depth, and as $\alpha = \frac{2\,\overline{DB}}{d}$, the intersections give also values of the constant α in (49).

d	$2\,\overline{DB}$	α
0.08	0.30	3.7
.10	.24	2.4
.12	.325	2.7
.143	.36	2.5

As the plotted dots are so irregular as to admit of much latitude in the drawing of the lines, these values of the constant are far from precise. No inference may be drawn from their differences, and collectively they serve only to indicate an order of magnitude. For fine sand, with slopes of about 1 per cent, the constant α has a probable magnitude of 2 or 3.

CAPACITY AND DEPTH.

To consider separately the response of capacity to variation of depth, the assumption of constant discharge and variable width must again be laid aside, and there must be substituted for it the assumption of constant width and slope, with variable discharge. That is, we are to conceive a stream of constant width, of which the discharge and load are simultaneously varied in such way as to maintain the slope unchanged, and the changes in depth are to be compared with the changes in load or capacity. To make the results strictly coordinate with those for the control of capacity by width, we should deal only with channels so broad and shallow that the lateral portions (fig. 39) are small in comparison with the medial portions, but this is not practicable. It is possible, however, to minimize the influence of lateral retardation by selecting groups of data in which the form ratio is small.

Table 25 contains data pertaining to débris of grade (C), a channel width of 0.66 foot, and a slope of 1 per cent. The values of capacity are taken from Table 12 and the values of depth from Table 14. It appears by inspection that the capacity increases with the depth. On plotting the pairs of values on logarithmic section paper, it is found that they may be represented approximately by a straight line. The examination of many such plots showed that the most accurate representative line has a gentle curvature, but for the present purposes it suffices to assume that the line is straight. That is to say, it is found to be approximately true, and the assumption is made, that C varies with some power of d, or

$$C \propto d^{m_1} \text{ .... } (50)$$

In the particular case $m_1 = 1.90$, and other values of m_1 are shown in Table 26.

TABLE 25.—*Values of capacity and depth for currents transporting débris of grade (C), when the width is 0.66 foot and the slope 1.0 per cent.*

Discharge (ft.³/sec.)	0.093	0.182	0.363	0.545	0.734
Capacity (gm./sec.)	13.8	32.1	73	112	152
Depth (foot)	.079	.110	.173	.228	.255

TABLE 26.—*Values of m_1 in $C \propto d^{m_1}$, when slope is constant.*

Grade.	Slope. (per cent).	Value of m_1 when width (feet) is			
		0.66	1.00	1.32	1.96
(C)	0.6	2.20	2.50	3.10	3.41
	1.0	1.90	2.10	2.32	2.97
(G)	1.0	2.67	2.96	3.95	....
	1.6	2.05	3.43	2.83	....
	2.4	1.80	2.26	2.48	....

Comparison of the tabulated values of m_1 shows that they have considerable range and that their variations in magnitude are definitely related to several conditions. The sensitiveness of capacity to variation of depth (when width and slope are constant) is greater as the slope is less, is greater as the fineness is less, and, with one exception, is greater as the width is greater:

$$m_1 = f\,(\grave{S},\ \grave{F},\ \acute{w}) \text{ .... } (51)$$

As w is by postulate constant, and as $d = w\,R$, it follows that $d \propto R$. R may therefore be substituted for d in proportion (50), giving

$$C \propto R^{m_1} \text{ .... } (52)$$

This is an expression for the relation of capacity to form ratio, so far as that relation depends on variation of depth. It is the complement of proportion (49) on page 126.

CAPACITY AND FORM RATIO.

We now return to the assumption of constant discharge. Having obtained an approximate expression for the law of capacity's variation in response to change of width and a coordinate expression for variation on response to change of depth, we next inquire how these may be combined into an expression for the response of capacity to simultaneous changes of width and depth, when those changes are of such character as to leave discharge constant.

If the functions (49) and (52) be assumed to be independent, their simple and direct combination gives

$$C \propto \frac{1-\alpha R}{R} R^{m_1} \text{ .... } (53)$$

This formula, as may readily be shown, satisfies an important condition by providing for a maximum value of C, but the assumption involved in its construction is not strictly warranted. The law embodied in $\frac{1-\alpha R}{R}$ is based on the constancy of d and may not be valid when d is made variable, while the law embodied in R^{m_1} may not be valid when w is made variable.

Viewing the matter from another side, we may say that the difficulty would not exist if the values of α and m_1 depended only on fineness, slope, and discharge and were independent of R; but they are in fact functions of R. (We have already seen that m_1 is an increasing function of w, and the variation of α with d

will appear in another connection.) An inquiry as to the nature of the functions—an inquiry here unrecorded except as to its result—served to determine that the variations of α and m_1, as functions of R, affect capacity in opposite senses, so that their influences are at least partly compensatory. It appeared also that each influence is relatively great when R is large and relatively small when R is small, so that their laws of distribution include a compensatory factor.

Despite the existence of this difficulty, which is palliated rather than cured by features of compensation, the function in (53) has been adopted as the best practicable formula for the relation of capacity to form ratio. The logical defect in the combination of its two factors may mean that its accuracy is inferior to that of the factors; but as the factors are confessedly only approximate, the defect is not inconsistent with the possession of even superior accuracy by the combination. In the treatment of so intricate a subject by methods which are dominantly empiric altogether adequate formulation is not to be hoped for; but the modicum of physical foundation afforded to formula (53) is believed to give it advantage over a purely mathematical expedient.

A slight transformation gives it more convenient form. Moving R from the denominator to the numerator and making $m_1 - 1 = m$, we have

$$C \propto (1 - \alpha R)\, R^m$$

It is convenient also to change from a proportion to an equation; introducing a coefficient, b_2,

$$C = b_2\, (1 - \alpha R)\, R^m \text{ - - - - - - - - } (54)$$

As R is a ratio between lengths, and α (p. 125) is also a numerical quantity without dimensions, b_2 is of the unit of C. It is the value of capacity when $(1 - \alpha R)\, R^m = 1$.

Let us now consider the properties of the formula. For the sake of giving a visible illustration, it has been applied to the example already used in figure 38. As the equation has three parameters, its constants require for their determination three pairs of values of R and C. The example furnishes four pairs, and these, by approximate adjustment, give

$$C = 346\, (1 - 2.18\, R)\, R^{0.52} \text{ - - - - - } (55)$$

The corresponding curve is shown in figure 41.

This conforms to the physical conditions by indicating two values of R for which capacity is nil, and an intermediate value for which capacity is at maximum. On referring to (54), it is evident that $C = 0$ when $R = 0$, and also when $1 - \alpha R = 0$, or $R = \frac{1}{\alpha}$.

In ascribing finite capacity to all small values of R the formula is inaccurate, for when the form ratio is gradually reduced the velocity must always fall below competence before the ratio reaches zero. The true function might be represented by some such curve as the broken line D in the figure. It has not seemed advisable to complicate the formula by a modification which might remedy this defect.

In the region of the larger values of R the formula is subject to a qualification already mentioned on page 125. The larger values are associated with narrow channels, in which the influences of the side walls or banks are dominant. So far as the laboratory data give indication, the formula is applicable to these values; but the adjustment might be less satisfactory with channel walls of a different character.

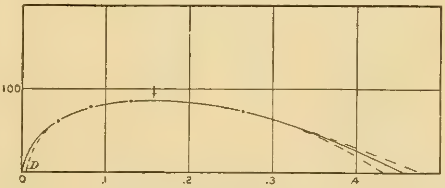

FIGURE 41.—Plot of equation (55). Capacity, vertical; form ratio, horizontal.

The region of the maximum value of capacity, which constitutes the chief field for the application of the formula, is little affected by the qualifications which have been mentioned.

Differentiating equation (54) and equating the first differential coefficient with zero, we have

$$b_2\, m\, R^{m-1} - b_2\, \alpha\, (m+1)\, R^m = 0$$

whence $R = \frac{1}{\alpha} \frac{m}{m+1}$, which is the condition giving C its maximum value. Designating this value of R by ρ, we have

$$\rho = \frac{1}{\alpha} \frac{m}{m+1} \text{ - - - - - } (56)$$

$$\alpha = \frac{1}{\rho} \frac{m}{m+1} \text{ - - - - - - - - - } (57)$$

Substituting from (57) into (54), we have

$$C=b_2\left(1-\frac{R}{\rho}\,\frac{m}{m+1}\right)R^m \text{.....}(58)$$

Equations (54) and (58) are alternative expressions of the same relation, the one involving α without ρ, the other ρ without α. Each has its field of superior convenience, alike for computations and discussion.

To obtain the maximum capacity, ρ is substituted for R in (58). The equation reduces to

$$C_{max}=\frac{b_2}{m+1}\rho^m \text{ ....}(59)$$

DISCUSSION OF EXPERIMENTAL DATA.

SCOPE AND METHOD OF DISCUSSION.

The equations adopted for the formulation of $C=f(R)$, namely, equations (54) and (58), involve four constants. b_2 is a quantity of the unit of capacity; ρ is a ratio, the form ratio corresponding to maximum capacity; α is a ratio connected with side-wall resistance; and m is an exponent. There is a mutual dependence between α and ρ; but b_2, α, and m, grouped together in (54), are independent; and so are b_2, ρ, and m, grouped in (58). In the following discussion of the relation of capacity to form ratio, equations of the form of (54) and (58) are derived from groups of experimental data; and these are compared in such way as to show the control of their constants by the conditions of slope, discharge, and fineness.

A "group" of experimental data, for this purpose, includes values of capacity and form ratio from at least three observational series, all pertaining to the same fineness, slope, and discharge, but to different widths. Three pairs of observational values suffice to determine the three independent parameters; with a greater number the problem is usually one of adjustment, to determine the most probable values of the parameters.

The computation of the constants by algebraic methods is tedious, and a graphic method was substituted. When an equation of the form of (58) is plotted on logarithmic section paper the shape and size of the curve are determined wholly by the exponent m: its position measured in the direction of the axis of log R is determined by the value of ρ; and its position with respect to the axis of log C by the value of b_2. A graphic process based on these properties gave solutions of sufficient approximation for the purposes of the discussion.

SENSITIVENESS AND THE INDEX OF RELATIVE VARIATION.

The sensitiveness of capacity to variation of form ratio is indicated graphically by the inclination of the logarithmic locus $C=f(R)$. As that locus is a curve, the sensitiveness varies with R. The form of the curve, as mentioned in the last paragraph, is determined by the exponent m, and the steepness (see fig. 42) of its legs varies directly with m. The exponent is thus a general index of sensitiveness.

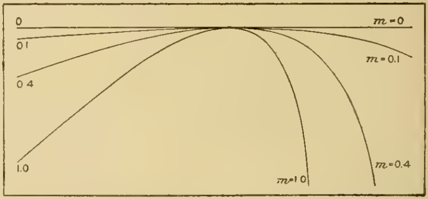

FIGURE 42.—Logarithmic plots of $C=b_2\left(1-\frac{R}{\rho}\,\frac{m}{m+1}\right)R^m$, corresponding to the same value of b_2 and ρ, but different values of m.

The logarithmic equivalent of (54) is

$$\log C=\log b_2+\log(1-\alpha R)+m\log R$$

Differentiating, we have

$$d\log C=d\log(1-\alpha R)+m\,d\log R$$

Dividing by d log R, we have

$$\frac{d\log C}{d\log R}=\frac{d\log(1-\alpha R)}{d\log R}+m$$

Making substitutions from

$$\frac{d\log C}{d\log R}=i_2$$

$$d\log(1-\alpha R)=\frac{-\alpha dR}{1-\alpha R}$$

and

$$d\log R=\frac{dR}{R}$$

and reducing, we have

$$i_2=m-\frac{\alpha R}{1-\alpha R}\text{ ....}(60)$$

It is evident that $\frac{\alpha R}{1-\alpha R}$ increases with increase of R; therefore i_2 decreases with increase of R. Also i_2 is positive when $m>\frac{\alpha R}{1-\alpha R}$ and negative when $m<\frac{\alpha R}{1-\alpha R}$. In passing from positive to negative, i_2 passes through zero when $m=\frac{\alpha R}{1-\alpha R}$ or when $R=\frac{1}{\alpha}\,\frac{m}{m+1}=\rho$ (cf. equation 56). When $R=0$, the limiting condition for a broad, shallow stream, $\frac{\alpha R}{1-\alpha R}=0$ and $i_2=m$. As this condition may only be approached but not reached, the positive values of the index are all less than m. When $\alpha R=1$, or $R=\frac{1}{\alpha}$, the condition limiting traction for a narrow, deep stream, $\frac{\alpha R}{1-\alpha R}=+\infty$ and $i_2=-\infty$. The negative values of the index therefore range to infinity.

The progressive changes of the index are conveniently illustrated by the characters of the curves in figure 42. Consider, for example, the curve corresponding to $m=1.0$. As this curve is the logarithmic locus of $C=f(R)$, its inclination to the horizontal represents i_2. At the extreme left, corresponding to a very small value of R (a shallow, wide stream), its inclination is a little less than 45°; or the value of i_2 is a little less than 1.0, the value of m. As the curve ascends i_2 is positive. The inclination then diminishes gradually and becomes zero at the apex of the curve, which corresponds to $R=\rho$. As the curve begins its descent the forward inclination corresponds to negative values of i_2, and these values increase numerically, becoming very large as the curve approaches verticality.

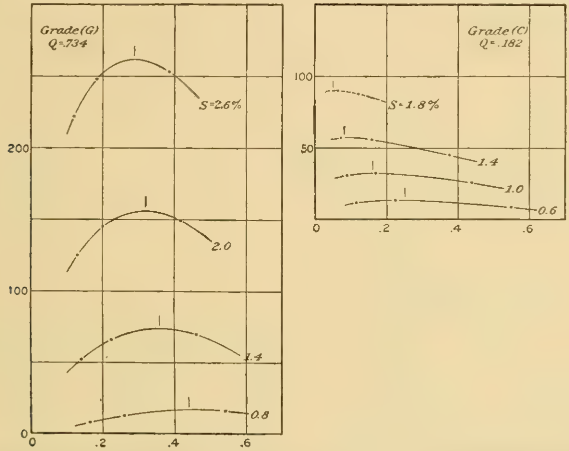

FIGURE 43.—Relation of capacity, C, to form ratio, R. The variation of the function $C=b_2(1-\alpha R)R^m$ with slope. Scale of C vertical; scale of R horizontal.

CONTROL OF CONSTANTS BY SLOPE.

To illustrate the way in which the index of sensitiveness and other constants defining the relation of capacity to form ratio are influenced by the condition slope, two sets of computations were made. The first set used data pertaining to débris of grade (C) and to a discharge of 0.182 ft.^{3}/sec.; the second, data for grade (G) and 0.734 ft.^{3}/sec. The observational data and the computed constants appear numerically in Table 27 and graphically in figure 43. The dots in the figure represent points fixed by the observations, and through these have been drawn curves conforming to formulas (54) and (58). Short vertical lines note the positions of the maxima, where $R=\rho$.

On referring to the table, it is seen that as the slope increases the values of m, ρ, and α decrease, while the value of b_2 increases. With steeper slopes of channel, capacity is relatively less sensitive to changes in the form of cross section; with steeper slopes, the form of section giving highest capacity for traction is relatively shallow and broad; with steeper slopes, the reduction of capacity through retardation of the current by the channel sides is relatively small; and the general effect of steepened slopes is increased capacity.

Each set of values of a constant exhibits an orderly progression, marred only by minor irregularities due to the inaccuracies of graphic computation. The results recorded in Tables 28 and 29 are much less orderly. It is to be noted that the remarkable orderliness in the present case is not due to high precision of the data but to the fact that the values of C and R assembled in Table 27 had previously been adjusted, as described in Chapter II, in a manner which made them orderly with respect to slope.

TABLE 27.—*Observed and computed quantities illustrating the influence of slope on the relation of capacity to form ratio.*

Grade and discharge (ft.³/sec.).	Observational data.				Constants of equations.				i_2
	Slope (per cent).	Width (feet).	Form ratio.	Capacity (gm./sec.)	m	ρ	α	b_2	
(C) 0.182	0.6	0.44	0.546	8.7	0.44	0.25	1.22	34.4	−1.55
		.66	.222	12.9					+ .07
		1.00	.113	11.4					+ .28
	1.0	.44	.436	24.7	.20	.158	1.05	55.5	− .65
		.66	.167	32.1					− .01
		1.00	.086	31.2					+ .10
	1.4	.44	.375	45.3	.08	.079	.94	75.2	− .46
		.66	.138	57.0					− .07
		1.00	.072	57.7					+ .01
	1.8	.66	.120	87	[.05	.05	.95	110]	− .08
		1.00	.063	90					− .01
(G) 0.734	.8	.66	.540	16.0	1.55	.44	1.38	170	−1.42
		1.00	263	13.3					+1.07
		1.32	.164	7.9					+1.26
	1.4	.66	.460	69	.80	.36	1.23	296	− .50
		1.00	.222	65					+ .42
		1.32	.141	52					+ .59
	2.0	.66	.418	149	.55	.32	1.11	451	− .32
		1.00	.199	145					+ .27
		1.32	.128	125					+ .41
	2.6	.66	.387	253	.45	.29	1.07	662	− .26
		1.00	.184	249					+ .20
		1.32	.120	222					+ .30

CONTROL OF CONSTANTS BY DISCHARGE.

Table 28 and figure 44 exhibit quantities and curves illustrating the influence of discharge on the relation of capacity to form ratio. The data employed are those of grade (C) with a channel slope of 1 per cent, and of grade (G) with a channel slope of 2 per cent. Of the seven curves in the figure, four were determined by three observational points. As three is the minimum number of given points for the determination of a curve of this type, each curve passes through all the points. In each of the other cases four points are given by the observations, and it was not found possible to pass one of the curves through all the points. If the formulas are correct, the incompatibility indicates errors of the data. Errors of similar magnitude inferably affect the three-point groups of data, and this inference qualifies the determination of the curves and their equations. Of the same general tenor is the fact that the four curves under grade (C), pertaining to discharges which increase in arithmetic progression, do not exhibit an orderly progression as to shape.

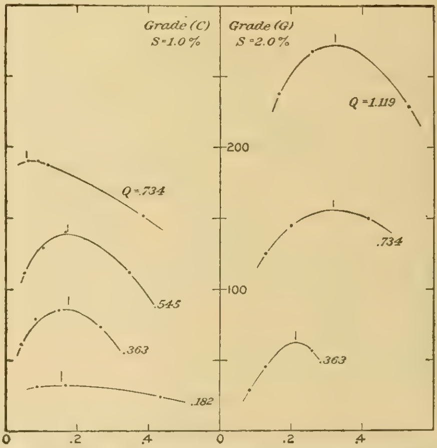

FIGURE 44.—Relation of capacity, C, to form ratio, R. The variation of the function $C=b_2(1-\alpha R)R^m$ with discharge. Scale of C vertical; scale of R horizontal.

Table 28.—*Observed and computed quantities illustrating the influence of discharge on the relation of capacity to form ratio.*

Grade and slope (per cent).	Observational data.				Constants of equations.				i_2
	Discharge (ft.³/sec.).	Width (feet).	Form ratio.	Capacity (gm./sec.).	m	ρ	α	b_2	
(C) 1.0	0.182	0.44	0.436	24.7	0.20	0.158	1.05	55.5	−0.65
		.66	.167	32.1					− .01
		1.00	.086	31.2					+ .10
	.363	.66	.264	73	.52	.157	2.18	340	− .84
		1.00	.130	85					+ .13
		1.32	.082	79					+ .30
		1.96	.043	60					+ .42
	.545	.66	.346	112	.40	.174	1.64	392	− .91
		1.00	.170	140					+ .01
		1.32	.104	129					+ .19
		1.96	.054	111					+ .30
	.734	.66	.386	152	.05	.061	.78	229	− .38
		1.00	.190	180					− .12
		1.32	.120	187					− .05
		1.96	.063	190					− .00
(G) 2.0	.363	.66	.260	56	1.52	.215	2.80	1,611	−1.15
		1.00	.128	45.2					+ .96
		1.32	.082	28.3					+1.22
	.734	.66	.418	149	.55	.320	1.11	451	− .32
		1.00	.199	145					+ .27
		1.32	.128	125					+ .41
	1.119	.66	.532	227	.58	.322	1.14	.830	− .96
		1.00	.260	268					+ .16
		1.32	.165	238					+ .35

The same incongruities of course characterize the tabulated numerical results. Increase of discharge is accompanied, in the main, by diminution of m and α, but the indications are inconclusive as to ρ and b_2.

CONTROL OF CONSTANTS BY FINENESS.

With reference to the influence of fineness of débris, the comparative data are restricted to three grades. Table 29 and figure 45 record the data and results for grades (B), (C), and (G), with use of a single slope and a single discharge. The curves for grades (B) and (C), which fall close together, are so different in form as to intersect; and the difference shown by the forms is otherwise expressed by incongruities among the values of constants. With the exception of b_2, the constants for grade (B) are intermediate between those of the other grades, whereas the intermediate grade is (C). If we ignore this incongruity and compare the constants for grades (B) and (C) with those for the coarse grade (G), we find that m, ρ, and α are all relatively small for the fine grades, or vary inversely with fineness, while b_2 varies directly with fineness. The variations of m and ρ are more pronounced than that of α.

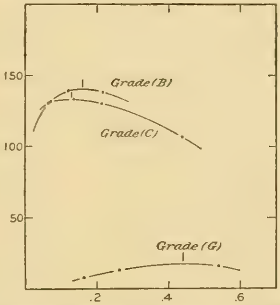

Figure 45.—Relation of capacity, C, to form ratio, R. The variation of the function $C=b_2(1-\alpha R)R^m$ with fineness of débris. Scale of C vertical; scale of R horizontal.

Table 29.—*Observed and computed quantities illustrating the influence of the fineness of débris on the relation of capacity to form ratio.*

Slope (per cent) and discharge (ft.³/sec.).	Observational data.				Constants of equations.				i_2
	Grade and fineness (F_2).	Width (feet).	Form ratio.	Capacity (gm./sec.).	m	ρ	α	b_2	
0.8 0.734	(B) 13,400	1.00	0.217	138	0.20	0.16	1.04	242	−0.09
		1.32	.120	139					+ .06
		1.96	.064	130					+ .13
	(C) 5,460	.66	.440	107	.12	.126	.85	191	− .48
		1.00	.214	130					− .10
		1.32	.134	133					− .01
		1.96	.070	131					+ .06
	(G) 5.9	.66	.540	16	1.55	.44	1.38	170	−1.42
		1.00	.263	13.3					+1.07
		1.32	.164	7.9					+1.26

SPECIAL GROUP OF OBSERVATIONS.

The special group of observations recorded in Table 4 (I), page 51, were arranged largely for the purpose of defining ρ, the optimum form ratio. They differed from the main body of observations in that the interval between the discharges employed and the interval between the widths employed were both smaller; and they were restricted to a single grade of débris. They had the advantage of an experimental method believed to be the best developed in the laboratory; and in view of this advantage their series were constituted of fewer individual observations than those of the main body of experiments. The results have not been satisfactory, and attempts at formulation in the present connection have developed marked incongruities. In figure 46 three curves are given, and the corresponding numerical data appear in Table 30. Each curve is based on five observational points, but they are so irregularly placed that their control is feeble.

On comparing the two cases having the same discharge, it is seen that the greater slope is associated with the smaller values of m, ρ, and α and with the greater value of b_2, the difference being most strongly marked for m and ρ. On comparing the two cases having the same slope, it is seen that the greater discharge is associated with the smaller values of m and ρ and with the larger value of b_2, while the values of α are nearly equal.

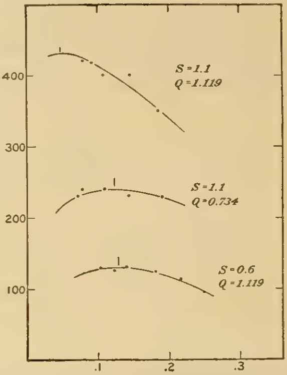

FIGURE 46.—Relation of capacity, C, to form ratio, R. Variation of the function $C=b_2(1-\alpha R)R^m$ with slope and discharge. Data from special group of experiments with débris of grade (C). Scale of C vertical; scale of R horizontal.

TABLE 30.—*Observed and computed quantities illustrating the influence of slope and discharge on the relation of capacity to form ratio.*

Grade.	Discharge (ft.³/sec.).	Observational data.				Constants of equations.				i_2
		Slope (per cent).	Width (feet).	Form ratio.	C	m	ρ	α	b_2	
(C)	0.734	1.1	1.0	0.190	230	0.3	0.123	1.88	586	−0.25
			1.2	.143	240					− .07
			1.4	.108	240					+ .05
			1.6	.079	231					+ .12
			1.8	.072	230					+ .14
	1.119	.6	1.2	.216	114	.5	.129	2.58	546	− .72
			1.4	.180	125					− .35
			1.6	.140	131					− .06
			1.8	.122	125					+ .05
			1.96	.102	130					+ .15
	1.119	1.1	1.2	.185	350	.1	.048	1.90	643	− .34
			1.4	.145	400					− .28
			1.6	.108	400					− .16
			1.8	.091	418					− .11
			1.96	.078	420					− .07

SUMMARY AS TO CONTROL BY CONDITIONS.

The treatment of the observational data by means of a formula specially designed to show the relation of capacity for traction to the proportions of the cross section develops incongruities. These are of such distribution as to indicate that they are due in chief part to the observations and their methods of adjustment. Discrepancies which manifestly pertain to the data are so large that it is not practicable to determine whether the imperfections of the formula are important.

The exponent m varies inversely with slope, with discharge, and with fineness. Thus all the conditions which tend to increase capacity tend also to make capacity less sensitive to changes in form ratio.

The optimum form ratio, ρ, varies inversely with slope and with fineness. As to its variation with discharge the evidence is not unanimous; either it varies inversely under some circumstances and directly under others, or else its proper variation is inverse and data of contrary import are erroneous. The latter view is thought more probable, because in many other connections the controls of slope and discharge follow parallel lines.

The constant α, which represents the resistance of side walls or banks to the flow of the stream, is also a decreasing function of slope, discharge, and fineness.

The constant b_2, which is of the unit of capacity, varies directly with slope and inversely with fineness, and the evidence as to its variation with discharge is conflicting. As b^2 is the value of capacity when

$$(1-\alpha R)\ R^m=1, \text{ or } \left(1-\frac{R}{\rho}\ \frac{m}{m+1}\right) R^m=1$$

it corresponds to a rather complicated relation between R, m, and α, or R, m, and ρ; and this relation makes the interpretation of the lack of order among its tabulated values a difficult matter.

If b_2 is left out of the account, it is possible to generalize by saying that the constants of equations (54) and (58) vary decreasingly with the conditions which affect capacity increasingly.

$$m=f(\grave{S},\ \grave{Q},\ \grave{F}) \qquad (61)$$
$$\rho=f_{\text{I}}(\grave{S},\ \grave{Q},\ \grave{F}) \qquad (62)$$
$$\alpha=f_{\text{II}}(\grave{S},\ \grave{Q},\ \grave{F}) \qquad (63)$$

THE OPTIMUM FORM RATIO.

The ratio of depth to width which gives to a stream its greatest capacity for traction is of importance to the engineer whenever he has occasion to control the movement of débris. The title *optimum ratio* is especially appropriate when his desire is to promote that movement.

The range of values for the ratio, under laboratory conditions, is from 1:2 to 1:20. One effect of this wide range, when taken in connection with the variety of conditions by which the ratio is controlled, is to complicate the formulation of practical rules; but this difficulty is not insuperable. It is qualified to an important degree by the consideration that capacity, in the region of its maximum, changes very slowly with change of form ratio, so that an approximate determination of the ratio has practical value.

The values of the ratio given in Table 31 are appropriate to the conditions of the Berkeley laboratory—that is, they pertain to troughs a few inches or a few feet wide, with smooth vertical sides. It is important to note also that they apply only to transportation of débris over a bed of débris, and not to flume traction, which has a different law. (See p. 213.)

TABLE 31.—*Estimated ratios of depth of current to width of trough, to enable a given discharge, on a given slope, to transport its maximum load.*

Material transported.	Slope (per cent).	Ratio for discharge (ft.³ sec.) of—			
		0.25	0.50	0.75	1.00
Fine sand	0.5	1:4	1:6	1:8	1:9
	1.0	1:6	1:9	1:12	1:15
	2.0	1:10	1:16	1:20	....
Coarse sand or fine gravel	1.0	....	....	1:25	1:3
	2.0	....	1:25	1:3	1:5
	3.0	1:2	1:3	1:4	1:7

No way has been found to extend the quantitative results to rivers. It can hardly be questioned that the optimum ratio for rivers varies inversely with slope, discharge, and fineness of débris, but its absolute amount can not be inferred from the experimental results. River slopes are relatively very small and river discharges are relatively very large, and the two differences affect the ratio in opposite ways. To compute the joint result we should have definite and precise information as to the laws of dependence, but our actual knowledge is qualitative and vague.

In this connection it is of interest to record a single observation on river efficiency. Where Yuba river passes from the Sierra Nevada to the broad Sacramento Valley its habit is rather abruptly changed. In the Narrows it is narrow and deep; a few miles downstream it has become wide and shallow. Its bed is of gravel, with slopes regulated by the river itself when in flood, and the same material composes the load it carries.

In the Narrows the form ratio during high flood is 0.06 and the slope is 0.10 per cent. Two miles downstream the form ratio is 0.008 and the slope is 0.34 per cent. Thus the energy necessary to transport the load where the form ratio is 0.008 is more than three times that which suffices where the form ratio is

0.06; and it is evident that the larger ratio is much more efficient than the smaller. The data do not serve to define the optimum form ratio, but merely show that it is much greater than 0.008. In this instance the slopes and fineness are of the same order of magnitude as those realized in the laboratory, but the discharges are of a higher order.

When water without detrital load is conveyed by an open rectangular conduit, the form ratio of highest efficiency is that which yields the highest mean velocity. It is approximately 1:2. This corresponds to the maximum value of the optimum ratio for traction, and the correspondence might have been expected on theoretic grounds. The two factors which, in ultimate analysis, determine capacity for traction are velocity of current along the bed and width of bed. When discharge and slope are such as barely to afford competence with the most favorable form ratio, that ratio is one giving the highest velocity, namely, 1:2. The other factor, width of bed, is evidently favored by lower values of R; and therefore, as the conditions recede from the limit of competence, the optimum form ratio becomes smaller. This line of reasoning might, in fact, have been used to show a priori—what has actually been shown by the experiments—that the value of ρ varies inversely with slope, discharge, and fineness.

SUMMARY.

Capacity for traction varies with the depth of the current, being approximately (though not precisely) proportional to a power of the depth. Capacity varies also with the width of the current, being approximately proportional to the width less a constant width. This constant width is equivalent to the product of the depth by a numerical constant. When the discharge is constant, any change of width causes a change of depth and also a change of form ratio, $R=\frac{d}{w}$. A formula for the variation of capacity in relation to form ratio, when the discharge is constant, is based on the above-mentioned properties and takes the form

$$C=b_2\ (1-\alpha\ R)\ R^m \quad \ldots \quad (54)$$

in which α is a numerical constant; or

$$C=b_2\left(1-\frac{R}{\rho}\ \frac{m}{m+1}\right)R^m \quad \ldots \quad (58)$$

in which ρ is the optimum form ratio, or the form ratio giving the highest capacity.

That capacity should have a maximum value corresponding to some particular value of form ratio is made to appear from theoretic considerations, and the fact of a maximum is shown by the experimental data. The same data show that the optimum form ratio has different values under different conditions, its values becoming smaller as slope, or discharge, or fineness increases.

The sensitiveness of capacity to the control of form ratio is indicated in the formulas by the exponent of R, and that also varies with conditions. It becomes smaller as slope, or discharge, or fineness increases.

It is believed that all the generalizations from the laboratory results may be applied to natural streams, but only in a qualitative way; the disparity of conditions is so great that the numerical results can not be thus applied.

CHAPTER V.—RELATION OF CAPACITY TO DISCHARGE.

FORMULATION AND REDUCTION.

As a condition controlling the capacity of a stream for the traction of débris, discharge is the coordinate of slope. Each of the two factors is proportional to the potential energy of the stream, on which traction depends; and the control of each is exercised through the control of velocity. Their fundamental difference in relation to traction is connected with depth of current. When velocity is augmented by increase of slope, the depth is reduced; when it is augmented by increase of discharge, the depth is increased. Notwithstanding this difference, the relations of capacity to discharge parallel those of capacity to slope to a remarkable extent. Thanks to this parallelism, the discussions of the present chapter may be based in considerable part on those which have preceded.

The data for the comparison of capacity with discharge are contained in Table 12. In each division of that table assigned to a grade of débris are a number of subdivisions pertaining severally to particular widths of channel. Each column of such a subdivision pertains to a particular discharge and contains a series of adjusted capacities corresponding to an orderly series of slopes. The values of capacity connected with the same slope and comprised in the same subdivision constitute a group illustrating the relation of capacity to discharge. Table 32 contains in its upper part a number of such groups, selected and arranged for the present purpose. So far as practicable they pertain to the same slope, but it was not possible to secure absolute uniformity in this respect and at the same time make the representation include data of all the grades of débris. For grades (A) to (E) the slope is 1.0 per cent; for grades (F) to (H), 1.2 per cent.

TABLE 32.—*Data on the relation of capacity to discharge, with readjusted values of capacity, C_r, and values of the index of relative variation, i_3.*

Conditions	Grade	(A)	(A)	(A)	(A)	(B)	(B)	(B)	(B)	(B)	(B)
	Slope (per cent)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Width (feet)	.66	1.00	1.32	1.96	.23	.44	.66	1.00	1.32	1.96
	Q	C	C	C	C	C	C	C	C	C	C
Data	0.093	[14.8]				7.8	13.2	10.8			
	.182	39.5	37.5	36.8		13.3	28.7	33.5	30.1	29.3	
	.363		100	104	96			81	85	79	67.6
	.545	140						120	143	140	120
	.734		231	250	240				199	204	190
	1.119				359						313
Adjusting equations	κ	.028	.048	.067	.105	.002	.017	.033	.057	.080	.125
	o	1.08	1.05	1.09	1.00	.79	1.00	1.13	1.12	1.06	1.08
	b_3	290	370	389	367	49.5	170	270	313	313	312
	Q	C_r	C_r	C_r	C_r	C_r	C_r	C_r	C_r	C_r	C_r
Readjusted capacities	0.093	15.1				7.8	13.2	11.1			
	.182	38.5	37.5	37.0		13.3	28.7	31.6	30.3	28.5	
	.363	89	99	103	96			77	83	83	67.6
	.545	142	167	174	159			127	140	140	123
	.734		231	250	234				201	201	185
	1.119				370						311
	Q	i_3	i_3	i_3	i_3	i_3	i_3	i_3	i_3	i_3	i_3
Index of relative variation	0.093	1.54				0.81	1.21	1.75			
	.182	1.28	1.43	1.72		.80	1.10	1.38	1.63	1.89	
	.363	1.17	1.21	1.33	1.41			1.24	1.33	1.36	1.64
	.545	1.14	1.15	1.24	1.24			1.20	1.25	1.24	1.40
	.734		1.12	1.20	1.17				1.21	1.19	1.30
	1.119				1.10						1.21
Probable error (per cent)	C							4.8	1.4	2.4	1.4
	C_r							2.4	0.7	1.2	0.7

Table 32.—*Data on the relation of capacity to discharge, with readjusted values of capacity, C_r, and values of the index of relative variation, i_3*—Continued.

Conditions	Grade	(C)	(C)	(C)	(C)	(C)	(D)	(D)	(D)	(E)
	Slope (per cent)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Width (feet)	.44	.66	1.00	1.32	1.96	.66	1.00	1.32	.66
	Q	C	C	C	C	C	C	C	C	C
Data	0.093	10.9	13.8				9.1			
	.182	24.7	32.1	31.2	21.4		29.8	24.0		
	.363		73	85	79	60		73	59.2	24.8
	.545		112	140	129	111	101	108		
	.734		152	180	187	190		153	131	40
	1.119			276		343				
Adjusting equations	κ	.020	.041	.071	.099	.156	.059	.102	.143	.108
	o	1.02	.94	1.00	1.05	1.14	.90	.88	.81	
	b_3	157	213	285	305	354	195	224	201	
	Q	C_r	C_r	C_r	C_r	C_r	C_r	C_r	C_r	C_r
Readjusted capacities	0.093	10.9	13.2				9.2			
	.182	24.7	33.9	33.0	22.0		29.6	24.3		
	.363		74	84	75	59	67	69	59.2	
	.545		112	135	130	120	102	110	97	
	.734		151	187	190	190		151	131	
	1.119			299		340				
	Q	i_3	i_3	i_3	i_3	i_3	i_3	i_3	i_3	i_3
Index of relative variation	0.093	1.30	1.68				2.46			
	.182	1.14	1.21	1.64	2.30		1.33	2.00		
	.363		1.06	1.24	1.44	2.00	1.07	1.22	1.33	
	.545		1.02	1.15	1.28	1.60	1.01	1.08	1.10	
	.734		1.00	1.11	1.21	1.45		1.02	1.01	
	1.119			1.07		1.32				
Probable error (per cent)	C		2.2	3.6	2.7	2.9		2.4		
	C_r		1.0	1.6	1.3	1.5		1.2		

Conditions	Grade	(E)	(E)	(F)	(F)	(F)	(G)	(G)	(G)	(H)
	Slope (per cent)	1.0	1.0	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Width (feet)	1.00	1.32	.66	1.00	1.32	.66	1.00	1.32	.66
	Q	C	C	C	C	C	C	C	C	C
Data	0.093									
	.182	14.8		9.3	4.2					
	.363	33.8	36.3	29.9	22.8	21.4	14.8	9.7		3.1
	.545									
	.734	72	73	55.3	63	61.6	48.3	44.0	33.8	24.6
	1.119	138	123		112	101	75	92	81	43.5
Adjusting equations	κ	.188	.263	.139	.242	.339	.199	.345	.433	.233
	o						.94			1.24
	b_3						.83			.54
	Q	C_r	C_r	C_r	C_r	C_r	C_r	C_r	C_r	C_r
Readjusted capacities	0.093									
	.182									
	.363						15.1			4.2
	.545									
	.734						46			22.5
	1.119						76			46
	Q	i_3	i_3	i_3	i_3	i_3	i_3	i_3	i_3	i_3
Index of relative variation	0.093									
	.182									
	.363						2.04			3.46
	.545									
	.734						1.29			1.82
	1.119						1.22			1.57
Probable error (per cent)	C									
	C_r									

The same data are plotted in figure 47, where horizontal distances represent logarithms of discharge and vertical distances logarithms of capacity. For each of the above-mentioned "groups" the plotted points are connected by a series of straight lines, and each of the broken lines thus produced is the rough logarithmic graph of an equation $C=f(Q)$. The graphs are arranged according to grades of débris, and secondarily according to widths of channel, their order from left to right corresponding to the sequence from narrower to broader channels. In effecting this arrangement graphs were moved bodily up or down but not to the right or left.

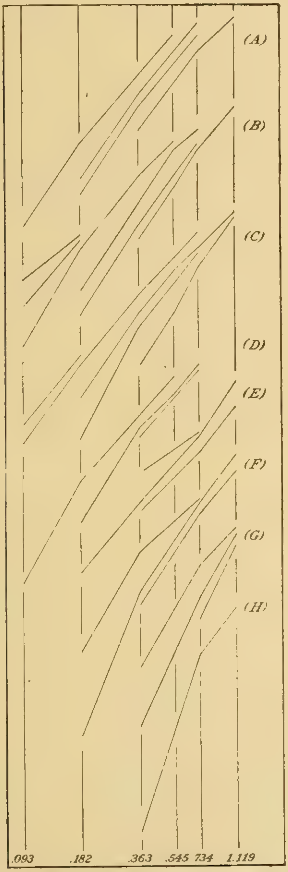

FIGURE 47.—Logarithmic plots of the relation of capacity to discharge. The horizontal scale is that of log Q, the vertical of log C. The zeros of log C for the different plots are not the same.

It appears by inspection that the graphs bend toward the right as they ascend. To this rule there are a few exceptions, but the only strongly marked exceptions are connected with grade (E), the data for which have previously been recognized as anomalous. As the inclination of each line indicates the sensitiveness of capacity to the control of discharge, the general bending to the right, or the reduction of inclination in passing from lower to higher discharges shows that sensitiveness diminishes as discharge increases. This feature is similar to one observed in studying the relation of capacity to slope, and as that feature was found to be connected with competence, the resemblance leads at once to the suggestion that here also is a connection with competence.

If a very small discharge be made to flow over a sloping bed of débris and the discharge be gradually increased, transportation of débris will commence when the competent discharge is reached and will increase with further increase of discharge. It is a plausible hypothesis that the capacity is more simply related to the excess of discharge above the competent quantity than to the total discharge. Following the procedure in the case of capacity and slope we may assume that capacity is proportional to a power of the excess of discharge above a constant discharge, the constant discharge being closely related to competent discharge. In the following formula, constructed on the plan of equation (10),

$$C=b_3\,(Q-\kappa)^o \text{ - - - - - - - - - - - - } (64)$$

κ is a constant discharge and b_3 is a constant numerically equal to the value of capacity when the discharge equals $\kappa+1$, although it is not strictly a capacity. The dimensions of capacity are $M^{+1}\,T^{-1}$, of discharge $L^{+3}\,T^{-1}$, and of $(Q-\kappa)^o$ $L^{+3o}\,T^{-o}$; and these values give to b_3 the dimensions $L^{-3o}\,M^{+1}\,T^{o-1}$.

As a preliminary to the adjustment of the observational data of Table 32 by this formula, values of κ were graphically computed by the method previously employed in connection with σ. The computations were applied to all groups of values of capacity in the table, except such as comprise less than three capacities and except also the aberrant data of grade (E). In Table 33 the results are arranged with reference to grade of débris and channel width.

TABLE 33.—*Values of the discharge constant, κ, computed from the discharges and capacities of Table 32.*

Grade.	Value of κ when width of channel (in feet) is—			
	0.66	1.00	1.32	1.96
(A)	....	0.070	0.075	0.215
(B)	0.056	.095	.035	.000
(C)	.025	.100	.030	.060
(D)	.060	.130	....	....
(F)	.149	.130	.180	....
(G)	.280	.160	....	....
(H)	.326	....	....	....

The tabulated values of κ show great irregularity. It is not difficult, however, to recognize a tendency to grow larger in passing from finer débris to coarser; and there is also, though it is ill defined, a tendency to increase with increasing width. The cause of the first-mentioned tendency is readily understood, because relatively coarse débris requires a relatively swift current to move it; and the reality of the second also finds support when the conditions affecting competent discharge are considered.

Postulating, initially, a channel of some particular width, containing a stream of which the discharge is barely competent, let us assume that the width is increased. In spreading to the new width the stream loses depth and velocity, and its velocity is no longer competent. That the velocity may again become competent the discharge must be increased. Thus it is in general true that competent discharge increases with increase of width. In the cross section of a broad laboratory current, figure 48, a medial portion, *AA*, is unaffected by side-wall resistance and has competent velocity. Two lateral portions, *AB*, have less than competent velocity. Let us imagine these lateral portions replaced by narrower divisions, *AD*, in which velocities are the same as in *AA*. The effective width for the maintenance of competent velocity is then $\overline{DD} = w - 2\,BD$. If now width and discharge be increased or diminished, with maintenance of competent velocity, the quantity $2\,\overline{BD}$ is unaffected, so that it may be regarded as a constant. Velocities being, by hypothesis, uniform through the whole space *DD*, the discharge is proportional to the width of that space.

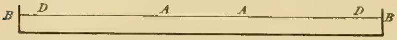

FIGURE 48.—Ideal cross section of a stream in the experiment trough, illustrating the relation of competent discharge to width.

$$Q_c \propto w - \text{a constant} \quad \text{..........(65)}$$

This result assumes a channel so wide that a medial portion is unaffected by side-wall resistance. It may not be true for narrower channels. If it were to be refined, the constant would be found to be a function of depth (compare p. 129); but in applying its principle to the values of κ no allowance was made for that factor.

On the theory that κ is closely related to competent discharge and has similar properties, and with the assumption that (65) may be applied to narrow channels as well as broad, the principle of (65) was used in adjusting the tabulated values of κ in relation to width of channel. The formula assumed was

$$\kappa \propto w - 0.2$$

The value of the constant was arbitrarily fixed, after several trials, no criterion for selection being discovered except the harmony of results.

With the aid of this formula it was possible to combine the data of Table 33 in such way as to afford a better view of the relation of κ to grade, or fineness; and this was done. By multiplication or division, each value was reduced to its equivalent for a channel width of 1 foot, and means were taken. These means appear in the second line of Table 34. They were compared with the mean diameters of particles for the several grades, the comparison being made on logarithmic section paper. In figure 49, showing this plot, the numbers indicate weights. While the plotted points do not fall well into line, they leave no question that the value of κ rises as the débris becomes coarser. On the assumption that the function is a power function, a straight line was drawn to represent it; and by this line the mean values of κ were adjusted. Values for the other trough widths were then computed. These appear in Table 32.

TABLE 34.—*Adjustment of system of values of κ for a channel width of 1 foot and slopes of 1.0 and 1.2 per cent.*

Grade	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
Mean diameter of particles (foot)	0.00100	0.00123	0.00166	0.00258	0.00561	0.01040	0.01620	0.02300
Mean κ computed from Table 33	.074	.078	.047	.117	....	.188	.367	.925
Adjusted κ	.048	.057	.071	.102	.188	.242	.345	.406

In making these adjustments due account was taken of the fact that not all the data used pertain to the same slope. Allowance for slope difference was made in plotting the values of κ to adjust for fineness, and again in applying the results of that adjustment. The adjustments for slope are based on the following consideration.

By use of the data in Table 12, values of κ pertaining to the same grade and width but differing as to slope were compared. In one case κ appeared to increase with increase of slope, but in most cases it appeared to decrease. Little weight, however, was given to such determinations, because it was evident that they were controlled by the values of σ, which had been somewhat arbitrarily assigned in the first adjustment of the observations. A more satisfactory indication was obtained by reasoning based on the relative sensitiveness of capacity to the several controls of slope and discharge. The index of relative variation of capacity with respect to slope being i_1, we may designate the corresponding index with respect to discharge by i_3. As capacity varies simultaneously with S^{i_1} and Q^{i_3} it is evident that for any particular value of capacity S^{i_1} and Q^{i_3} vary inversely. The proportion $Q^{i_3} \propto \frac{1}{S^{i_1}}$ yields

$$Q \propto \frac{1}{S^{\frac{i_1}{i_3}}}$$

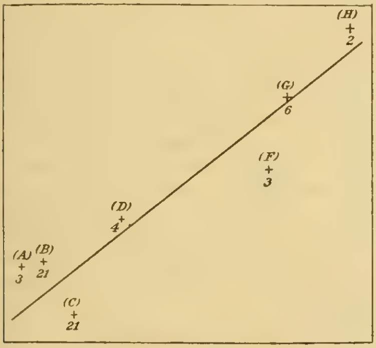

FIGURE 49.—Logarithmic plot of $\kappa = f(D)$.

From a discussion of the relations of the two indexes, to be found on a later page of the present chapter, it appears that the average ratio of i_1 to i_3 is 1.36 but that the ratio varies somewhat with conditions. For the condition $C=0$ it is assumed to be 1.3; or $\kappa \propto \frac{1}{S^{1.3}}$.

While considerable uncertainty attaches to the numerical relations, there can be no question that κ varies directly with width and inversely with fineness and slope. As any change in width affects the form ratio in the opposite sense, we may write

$$\kappa = f(\grave{S}, \grave{F}, \grave{R}) \text{ - - - - - - - - - - - } (66)$$

A system of values of κ having been thus arranged, logarithmic plots were made of the capacities of Table 32, in relation to $Q - \kappa$, and straight lines were drawn representing equations of the type of (64). In cases where the plotted points did not fall well in line, recourse was had to weights based on the probable errors recorded in Table 12. The lines thus drawn gave, by their inclinations and intersections, the values of the other parameters, o and b_3, as well as the adjusted values of capacity, C_r, all of which are presented in Table 32. The plots for data of grades (E) and (F) and for two of the three groups under grade (G) exhibited so great irregularities that it was decided not to use them.

The similarity of equation (64) to equation (10) makes it unnecessary to repeat the reasoning by which (38) was educed, and the equation for the index of relative variation for capacity in relation to discharge may be written directly:

$$i_3 = \frac{oQ}{Q - \kappa} \text{ - - - - - - - - - - - - } (67)$$

By its use the values of i_3 in Table 32 were computed.

MEASURES OF PRECISION AND THEIR INTERPRETATION.

In 16 of the columns of Table 32 the values of capacity before and after adjustment constitute data suitable for the computation of probable errors. As the number of residuals is in each case small, the particular values of probable errors (recorded at the bottom of the table) are not themselves of high precision; but the averages have greater claim to attention. It should be added that the residuals were treated as of equal weight, despite the fact that in the adjustment which determined them the relative weights of the observational data were recognized.

The probable errors of the upper line, marked "C," pertain to the adjusted values of capacity taken from Table 12, which are here treated as observations. The probable errors of the lower line, marked "C_r," pertain to the groups of readjusted values of capacity.

The average probable error (or, strictly, the mean of the nine tabulated errors) of the readjusted capacities is ±1.3 per cent. The corresponding average for the capacities before readjustment is ±2.64 per cent.

It is of interest to compare the last figure with the previously computed average probable error of the adjusted values of capacity in Table 12, namely, ±2.50 per cent. The earlier estimate applies to 66 series of values, the later to 36 values taken from 36 of the series. The 36 values may be regarded as properly representative of the series from which they come. Of the unrepresented series, a portion escaped because the values they furnished to Table 32 fell in groups of less than four, and such a group did not afford suitable data for computation of probable error. The others were omitted because the groups they constituted involved incongruities so great that they were rejected in the readjustment. The omission of incongruous groups evidently had the effect of lowering the estimate of average probable error, and to give validity to the comparison due allowance should be made for that effect. The discarded values were accordingly treated so far as necessary to compute their probable errors, and it was found that by the inclusion of these the estimate of average probable error was raised from 2.64 to 3.2 per cent. The revised estimate is believed to be properly comparable with the earlier estimate of 2.50 per cent. It will be recalled that the original observations were characterized by accidental errors, ascribed chiefly to rhythm, and by systematic errors, ascribed chiefly to methods of observation. The nature of the first adjustment was such that its computed probable errors were little affected by the errors of the second class. The adjustment was conditioned by a formula involving the assumption that capacity varies as a power of $(S-\sigma)$, and also by various assumptions involved in the arrangement of a system of values for σ. Whatever errors were introduced in connection with these assumptions tended to increase the estimates of probable error; but they may also be supposed to have aggravated somewhat the errors of the class not covered by the computations of probable error.

The errors falling outside the estimates of probable error were largely of such nature as to affect an observational series in its entirety, and it was expected that they would be revealed in the failure of groups of quantities taken from different series to exhibit an orderly sequence. Abundant evidence of their existence has been encountered in various discussions, including the control by conditions of the sensitiveness of capacity to slope, of the sensitiveness of capacity to form ratio, of the value of the optimum form ratio, and of the value of the constant κ; but the present discussion is the only one affording an estimate of their magnitude.

Assuming that the estimate of 2.5 per cent represents the influence of a restricted class of errors, and that the estimate of 3.2 per cent represents the joint influence of that class and a second class, the independent influence of the second class is represented by

$$\sqrt{3.2^2-2.5^2}=\pm\ 2.0 \text{ per cent}$$

The indication is that the two classes of errors are of nearly equal importance.[1]

These results are qualified by the fact that the estimate of 3.2 per cent includes not only the errors of the adjusted values of capacity in

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[1] The considerations making it probable that ±2.5 per cent is an overestimate for the average error of the first class (p. 74) do not apply to the estimate of ±3.2 for the combined error. If the average error for the first class is as low as ±2.0 per cent, the computed average for the second class becomes ±2.5 per cent.

Table 12, but also whatever errors affect the method of adjustment in connection with the discussion of the control of capacity by discharge. That method includes the assumption that capacity varies as a power of $(Q-\kappa)$ and also certain assumptions as to the control of κ by various conditions. If the errors involved in those assumptions could be eliminated or discriminated, the general estimate for the values in Table 12 would be somewhat reduced.

As the chief result of this discussion, the general precision of the main body of material contributed by the Berkeley experiments is characterized by an average probable error slightly in excess of 3 per cent.

This estimate applies specifically to the adjusted capacities of Table 12 as those capacities are related to slope and discharge, and it can not be extended to derivatives of those capacities without qualification. It is believed that the precision of the readjusted capacities of Table 32 is higher, and also that of the values of I_1 in Table 23, but that the values of i_1, j_1, and i_3, in Tables 15, 16, and 32, rank lower.

In the adjustment of the observations on capacity in relation to slope, and also in the adjustment of observations on depth and slope, many cases were treated in which the observations were either not sufficiently numerous or not sufficiently harmonious to afford good control of the parameters of the adjusting equations. In such cases the parameters were estimated in groups, with orderly sequences of values. A similar method was employed also in readjustments in relation to discharge. While this procedure appeared, and still appears, to be the best practicable, it can hardly fail to introduce a certain amount of error. The terms of the adjusted sequences are inevitably associated with different form ratios; and the laws connecting form ratio with capacity are so different from the other laws of the system as to determine sequences less simple than those actually used. The ideal adjustment would take simultaneous cognizance of the complicated interrelations of capacity, slope, discharge, and form ratio; but such comprehensive treatment can not be attempted with profit until we have a better theoretic knowledge of the physical reactions.

CONTROL OF RELATIVE VARIATION BY CONDITIONS.

The sensitiveness of capacity to changes of discharge is indicated by i_3, the index of relative variation. Inspection of the values of that index recorded in Table 32 shows that they vary inversely with discharge and directly with width, and both these tendencies are also to be inferred from the lines of figure 47.

The table further indicates that the rate of change in the index in response to change of discharge is greater for small discharges than for large. This feature might also have been inferred from the plotted lines, but its systematic expression in the table is a product of the formula, $i_3=\frac{oQ}{Q-\kappa}$, by which the values were computed.

The relation of the index to width of channel is not similarly dominated by the formula, although somewhat influenced by the assignment of values of κ. The variation of the index with width is in general more pronounced for low discharges than for high, but in the data for high discharges occur two exceptions to the general law. These exceptions are ascribed to irregularities in the data. As the width for any particular discharge varies inversely with the form ratio, it follows that the index is a decreasing function of form ratio.

The relation of the index to slope is not shown by the table. It was the subject of a special inquiry, including 32 comparisons. In each comparison a value of the index for a particular slope was contrasted with the value for a slope twice as great, the other conditions being the same. In 25 instances the greater index was associated with the smaller slope; in 7 instances with the larger. The mean of the indexes computed for smaller slopes was 1.51; the mean for larger slopes 1.17. The general law appears to be that the index varies inversely with slope. The seven instances of opposite tenor are all associated with large discharges; and their occurrence is ascribed to a systematic error connected with the assignment of values to κ.

Table 35 compares values of the index with fineness. Despite irregularities, it is evident that the values tend to increase in passing from finer to coarser grades—that is, their variation in respect to fineness is inverse.

Table 35.—*Values of the exponent i_3 arranged to show variation in relation to fineness of débris.*

Grade.	Values of i_3.				
	$Q=0.363$			$Q=0.182$	
	$w=0.66$	$w=1.00$	$w=1.32$	$w=0.66$	$w=1.00$
(A)	1.17	1.21	1.33	1.28	1.43
(B)	1.24	1.33	1.36	1.38	1.63
(C)	1.06	1.24	1.44	1.21	1.64
(D)	1.05	1.25	1.33	1.30	2.02
(G)	2.04	....	....	....	....
(H)	3.46	....	....	....	....

In summary, the sensitiveness of capacity to variation of discharge is greater as slope, discharge, form ratio, and fineness are less.

$$i_3=f\,(\grave{S},\ \grave{Q},\ \grave{F},\ \grave{R})\quad\text{.........}\quad(68)$$

DUTY AND EFFICIENCY.

The variation of capacity with discharge is indicated in general terms by an equation of the type of (33):

$$C=v_3Q^{i_3}\quad\text{..............}\quad(69)$$

Duty being the quotient of capacity by discharge, this gives

$$U=\frac{v_3Q^{i_3}}{Q}=v_3Q^{i_3-1}\quad\text{.........}\quad(70)$$

and, as efficiency is the quotient of capacity by discharge and slope,

$$E=\frac{v_3}{S}\,Q^{i_3-1}\quad\text{............}\quad(71)$$

That is, the index of relative variation for both duty and efficiency, in relation to discharge, is less by unity than the corresponding index for capacity. Therefore the values of the index in Table 32 need only to be reduced by unity to apply to duty and efficiency.

Under ordinary conditions the index for duty and efficiency falls between unity and zero; or, in other words, duty and efficiency increase with increase of discharge, but their increase is less rapid than that of discharge. Exceptionally the increase is much more rapid, the exceptions being associated with discharges little above the limit of competence. On the other hand, there appear to be conditions under which the index falls below zero, so that duty and efficiency diminish with increase of discharge. The diminution indicated by the figures in the column (of Table 32) for grade (D) and width 0.66 foot is only of the order of magnitude of the probable error; but a pronounced diminution would be inferred from the values of the index for grade (B) and width 0.23 foot. As the results from the last-mentioned group of observations stand by themselves in various respects, some reservation is felt in regard to them, and there is at least room for doubt whether the diminution is actually demonstrated.

With respect to all conditions the variations of the index for duty and efficiency follow the same laws as the index for capacity; but, as a consequence of the uniform reduction by unity, the rates of variation are higher. If, for example, in passing from a smaller to a larger discharge, the index for capacity falls from 1.40 to 1.20, a reduction of one-seventh, the index for efficiency falls from 0.40 to 0.20, a reduction of one-half.

Lines of reasoning strictly parallel to those employed in the last section of Chapter III yield the following conclusions:

The synthetic index of relative variation for the duty of water in relation to discharge is less by unity than the corresponding synthetic index for capacity in relation to discharge.

The synthetic index of relative variation for efficiency in relation to discharge is less by unity than the corresponding synthetic index for capacity in relation to discharge.

If the duty of water, or if efficiency, be assumed to vary as some power of $Q-\kappa$, the exponent of that power (expressing the instantaneous rate of variation) equals $o-\frac{Q-\kappa}{Q}$. As discharge increases from κ toward infinity, the exponent diminishes from o toward $o-1$.

If the relation of efficiency to discharge (and similarly for the relation of duty to discharge) be expressed by

$$E=B_1(Q-\kappa_1)^{o_{\text{II}}}\quad\text{..........}\quad(71a)$$

the value of o_{II} is always less than the corresponding value of o, the difference approaching but not exceeding unity. The value of κ_1 is always greater than the corresponding value of κ, usually much greater. It was found by trial that, within the range of conditions realized in the laboratory, the difference between values of efficiency computed directly by means of (71a) and values computed indirectly by means of (64) is not large, its order of magnitude being that of the probable errors.

The control of duty and efficiency by discharge is further considered in the following section.

COMPARISON OF THE CONTROLS OF DISCHARGE AND SLOPE.

CONTROLS OF CAPACITY.

We are now in position to compare the influences exerted by slope and discharge, severally, on capacity. The general fact brought out by the comparison is that capacity is more sensitive to changes of slope than to changes of discharge, but the difference in sensitiveness is not the same for all conditions.

TABLE 36.—*Comparison of the index of relative variation, i_1, for capacity and slope, with the index, i_3, for capacity and discharge.*

[For grades (A) to (D) the data are for $S=1.0$; for grades (G) and (H) for $S=1.2$.]

Grade.	Q	$w=0.44$		$w=0.66$		$w=1.00$		$w=1.32$		$w=1.96$	
		i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3
(A)	0.182	....	....	1.99	1.28	2.06	1.43	2.17	1.72	....	....
	.363	....	....	....	....	1.83	1.21	1.70	1.33	1.90	1.41
	.545	....	....	1.48	1.14	....	....	....	....	....	....
	.734	....	....	....	....	1.79	1.12	1.71	1.20	1.55	1.17
	1.119	....	....	....	....	....	....	....	....	1.31	1.10
(B)	.093	2.31	1.21	2.34	1.75	....	....	....	....	....	....
	.182	1.81	1.10	1.82	1.38	1.92	1.63	1.94	1.89	....	....
	.363	....	....	1.58	1.24	1.67	1.33	1.75	1.36	2.01	1.64
	.545	....	....	1.49	1.20	1.62	1.25	1.73	1.24	1.87	1.40
	.734	....	....	....	....	1.61	1.21	1.71	1.19	1.66	1.30
	1.119	....	....	....	....	....	....	....	....	1.60	1.21
(C)	.093	2.39	1.30	1.88	1.68	....	....	....	....	....	....
	.182	1.88	1.14	1.73	1.21	1.87	1.64	2.37	2.30	....	....
	.363	....	....	1.59	1.06	1.59	1.24	1.67	1.44	2.14	2.00
	.545	....	....	1.58	1.02	1.47	1.15	1.55	1.28	1.87	1.60
	.734	....	....	1.57	1.00	1.45	1.11	1.47	1.21	1.62	1.45
	1.119	....	....	....	....	1.48	1.07	....	....	1.85	1.32
(D)	.093	....	....	2.22	2.46	....	....	....	....	....	....
	.182	....	....	1.80	2.33	2.01	2.00	....	....	....	....
	.363	....	....	....	....	1.69	1.22	2.11	1.33	....	....
	.545	....	....	1.64	1.01	1.87	1.08	....	....	....	....
	.734	....	....	....	....	1.65	1.02	1.85	1.01	....	....
(G)	.363	....	....	2.98	2.04	....	....	....	....	....	....
	.734	....	....	2.42	1.29	....	....	....	....	....	....
	1.119	....	....	2.29	1.22	....	....	....	....	....	....
(H)	.363	....	....	6.03	3.46	....	....	....	....	....	....
	.734	....	....	3.23	1.82	....	....	....	....	....	....
	1.119	....	....	2.78	1.57	....	....	....	....	....	....

In Table 36 values of the index of relative variation are brought together from Tables 15 and 32. The selection includes all such as correspond in respect to débris, trough width, slope, and discharge, with the exception of those of trough width 0.23 foot, which appear to be anomalous. There are 64 pairs of values.

Of the 64 comparisons, 62 show capacity as more sensitive to slope, 2 as more sensitive to discharge. The two exceptional cases are from experiments with débris of grade (D) and with channel width 0.66 foot; and the data from those experiments were reexamined in search for an explanation of what seems an anomaly. No explanation was found, and, as the observations are supported by the estimates of precision, it remains probable that there are real exceptions to the general rule.

The means of the 64 values of i_1 and i_3 are, severally, 1.93 and 1.42; and the ratio of the first to the second is 1.36. On the average, the sensitiveness of capacity to slope is one-third greater than the sensitiveness of capacity to discharge.

To ascertain the variation of the ratio $\frac{i_1}{i_3}$ with discharge, the values in Table 36 were specially grouped for the taking of partial averages. The first group gave comparative ratios for discharges of 0.093 and 0.182 ft.^{3}/sec., by means of four sets of index values, each set agreeing as to all conditions other than discharge. The second group gave comparative ratios for discharges of 0.182, 0.363, and 0.734 ft.^{3}/sec., by means of five sets of index values; and two other groups made other comparisons, as shown in Table 37. The upper division of the table gives mean values of i_1 and i_3; the lower division, their ratios. It will be observed that within each group the values of the indexes decrease as discharge increases, while the values of the ratio, as a rule, increase with the increase of discharge. To the first rule there are no exceptions; the exceptions to the second are not so important as to leave the principle in doubt.

TABLE 37.—*Variations of the indexes i_1 and i_3, and their ratio, in relation to discharge.*

Group.	Sets.	$Q=0.093$		$Q=0.182$		$Q=0.363$		$Q=0.545$		$Q=0.734$		$Q=1.119$	
		i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3
1	4	2.23	1.48	1.81	1.21	....	....	....	....	....	....	....	....
2	5	....	....	2.02	1.74	1.73	1.30	....	....	1.65	1.16	....	....
3	8	....	....	....	....	1.76	1.41	1.69	1.26	1.59	1.19	....	....
4	7	....	....	....	....	2.67	1.97	....	....	1.97	1.32	1.85	1.22
		i_1/i_3		i_1/i_3		i_1/i_3		i_1/i_3		i_1/i_3		i_1/i_3	
1	....	1.50		1.50		....		....		....		....	
2	....	....		1.16		1.33		....		1.42		....	
3	....	....		....		1.25		1.35		1.34		....	
4	....	....		....		1.35		....		1.49		1.52	

The variations of the indexes with discharge have already been illustrated in another way (pp. 107, 143). The new fact brought out is that the superiority of slope over discharge, as a factor controlling capacity, is more pronounced for large discharges than for small, under like conditions of slope, width, and fineness.

TABLE 38.—*Variations of the indexes i_1 and i_3, and their ratio, in relation to width of channel.*

Group.	Sets.	$w=0.44$		$w=0.66$		$w=1.00$		$w=1.32$		$w=1.96$	
		i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3
1	4	2.10	1.19	1.94	1.50	....	....	....	....	....	....
2	8	....	....	1.67	1.17	1.71	1.35	1.83	1.55	....	....
3	8	....	....	....	....	1.63	1.20	1.66	1.28	1.83	1.50
		i_1/i_3		i_1/i_3		i_1/i_3		i_1/i_3		i_1/i_3	
1	....	1.77		1.29		....		....		....	
2	....	....		1.40		1.27		1.18		....	
3	....	....		....		1.36		1.30		1.22	

A different grouping of the index values, but similar in principle, gave the means and ratios of Table 38, which is related to channel width just as Table 37 is related to discharge. With a single exception, the mean values of indexes increase with width; thus illustrating general facts previously noted on pages 104 and 143. Without exception, the ratios of i_1 to i_3 decrease with increase of width. The new fact brought out is that the superiority of slope over discharge, as a factor controlling capacity, is more pronounced for narrow channels than for wide, under like conditions of slope, discharge, and fineness.

As form ratio varies inversely with width, it follows that the superiority of slope is more pronounced, under like conditions, when form ratio is large than when it is small.

A third grouping of the index values, making a similar comparison of their averages and ratios with fineness of débris, is reported in Table 39 (p. 147). The mean values of indexes increase on the whole in passing from finer to coarse grades, but there is much irregularity. The same irregularity was encountered when these relations were examined in other connections. (See pp. 108 and 143.) The ratios decrease on the whole from finer to coarser, and there is but one discordance among the sequences.

To compare the variations of the indexes with changes in slope, the 32 pairs of values of

i_3 mentioned on page 143 were contrasted with corresponding values of i_1. The results are summarized in Table 40, below, in which each of the three groups indicates that the ratio of the indexes increases with increase of slope.

Table 39.—*Variations of the indexes i_1 and i_3, and their ratio, in relation to fineness of débris.*

Group.	Sets.	(A)		(B)		(C)		(D)		(G)		(H)	
		i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3
1	11	1.77	1.28	1.74	1.39	1.76	1.45	......	......	......	......	......	......
2	8	......	......	1.79	1.38	1.65	1.32	1.87	1.54	......	......	......	......
3	3	......	......	......	......	......	......	......	......	2.70	1.60	4.63	2.64

Group.	Sets.	(A) i_1/i_3	(B) i_1/i_3	(C) i_1/i_3	(D) i_1/i_3	(G) i_1/i_3	(H) i_1/i_3
1	......	1.38	1.25	1.21	......	......	......
2	......	......	1.30	1.26	1.21	......	......
3	......	......	......	......	......	1.69	1.76

Table 40.—*Variations of the indexes i_1 and i_3, and their ratio, in relation to slope.*

Group.	Sets.	$S=0.5$		$S=1.0$		$S=1.2$		$S=2.0$		$S=2.4$	
		i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3	i_1	i_3
1	18	1.90	1.56	1.68	1.23	......	......	......	......	......	......
2	10	......	......	1.87	1.45	......	......	1.66	1.12	......	......
3	4	......	......	......	......	2.82	1.47	......	......	2.13	1.08

Group.	Sets.	$S=0.5$ i_1/i_3	$S=1.0$ i_1/i_3	$S=1.2$ i_1/i_3	$S=2.0$ i_1/i_3	$S=2.4$ i_1/i_3
1	......	1.22	1.35	......	......	......
2	......	......	1.29	......	1.49	......
3	......	......	......	1.91	......	1.98

To sum the results of the preceding paragraphs: The sensitiveness of capacity for traction to changes of slope, as measured by the exponent i_1, is in general greater than its sensitiveness to changes of discharge, measured by i_3. The superiority of the control by slope persists through nearly (or perhaps quite) the entire range of conditions realized in the laboratory. If the superiority is measured by the ratio $\frac{i_1}{i_3}$, its average value (based on 64 comparisons) is 1.36, and it increases with increase of slope, discharge, form ratio, and fineness of débris.

$$\frac{i_1}{i_3}=f(\acute{S}, \acute{Q}, \acute{F}, \acute{R}) \text{ ....(72)}$$

Another mode of comparing the controls by slope and discharge is by means of the synthetic index of relative variation (p. 99), and in some respects this mode is more satisfactory than the one given above. The synthetic index, I_3, of the relative variation of capacity and discharge was computed for 21 cases, in each of which the greater discharge was approximately double the lesser. The synthetic index I_1, of the relative variation of capacity and slope, was computed for 21 pairs of cases, the greater slope being double the lesser. Each value of I_3 was joined to two discharges and a slope and associated with a pair of values of I_1. Each of the two values of I_1 was joined to one discharge and two slopes, the slopes being so chosen, whenever possible, that their mean coincided with the slope of the associated I_3. The mean of the 42 values of I_1 is 1.92; that of 21 values of I_3 is 1.42; and the ratio of these means is 1.35. The result is practically identical with that obtained by the discussion of values of i_1 and i_3.

CONTROLS OF DUTY.

The index of relative variation of the duty of water in relation to slope (p. 121) is i_1, the same as the index for capacity and slope. The corresponding index for the duty of water in relation to discharge (p. 144) is i_3-1. The ratio of these indexes, $\frac{i_1}{i_3-1}$, is evidently greater than the ratio $\frac{i_1}{i_3}$, which has just been considered—that is, the superiority of the control by slopes, as compared with the control by discharge, is more strongly marked in the case of duty than in the case of capacity.

For general averages, $\frac{i_1}{i_3}=\frac{1.93}{1.42}=1.36$, and $\frac{i_1}{i_3-1}=\frac{1.93}{0.42}=4.3$.

In Table 41 the values of $\frac{i_1}{i_3-1}$ correspond to those of $\frac{i_1}{i_3}$ in Tables 37 to 40—that is, they are based on the partial means of those tables and are arranged under the same groups, the purpose being to show how the dominance of control by slope, as expressed by a ratio, varies with certain conditions.

Table 41.—*Variations of the ratio $\frac{i_1}{i_3-1}$ in relation to discharge, width of channel, fineness of débris, and slope.*

		Values of $\frac{i_1}{i_3-1}$ for group—			
		1	2	3	4
$Q=$	0.093	4.6	....	....	....
	.182	8.6	2.7	....	....
	.363	....	5.8	4.3	2.8
	.545	....	....	6.5	....
	.734	....	10.3	8.4	6.1
	1.119	....	....	....	8.4
$w=$	0.44	11.2	....	....	....
	.66	3.9	9.8	....	....
	1.00	....	4.9	8.1	....
	1.32	....	3.3	5.9	....
	1.96	....	....	3.7	....
Grade	(A)	6.3	....	....	....
	(B)	4.5	8.0	....	....
	(C)	3.9	5.1	....	....
	(D)	....	3.5	....	....
	(G)	....	....	4.9	....
	(H)	....	....	3.1	....
$S=$	0.5	3.4	....	....	....
	1.0	7.3	4.2	....	....
	1.2	....	....	6.0	....
	2.0	....	13.8	....	....
	2.4	....	....	26.6	....

In comparing this table with the tables of $\frac{i_1}{i_3}$, the most conspicuous feature noted is that the variation of $\frac{i_1}{i_3-1}$ with all conditions is much more pronounced than the variation of $\frac{i_1}{i_3}$. Associated with this is the fact that the exceptions or apparent reversals observed in Tables 37 and 39 are not repeated in Table 41.

In verbal generalization of the tabulated results it is to be borne in mind (1) that the alphabetic order in which the grades are arranged is the order from fine to coarse, and (2) that variation with respect to form ratio is the inverse of variation with respect to width of channel. The general fact is that the dominance of control by slope, as compared with control by discharge—a dominance always pronounced—is notably increased by increase of slope, discharge, fineness, or form ratio.

$$\frac{i_1}{i_3-1}=f\,(\acute{S},\,\acute{Q},\,\acute{F},\,\acute{R})\ \ldots\ldots\ (73)$$

CONTROLS OF EFFICIENCY.

The index of relative variation of efficiency in relation to slope (p. 144) is i_1-1; and the corresponding index for efficiency in relation to discharge is i_3-1. The ratio of these indexes $\frac{i_1-1}{i_3-1}$ is greater than $\frac{i_1}{i_3}$, the corresponding ratio in the case of capacity, with exception of those doubtful cases in which $i_1<i_3$. That is, the superiority of the control by slope, as compared to the control by discharge, is more strongly marked in the case of efficiency than in the case of capacity. It is also true that $\frac{i_1-1}{i_3-1}<\frac{i_1}{i_3-1}$; or that the superiority of control by slope is less strongly marked for efficiency than for duty. For the general averages $i_1=1.93$ and $i_3=1.42$ the computed values of the ratios expressing superiority of control by slope are, as to capacity 1.36, as to efficiency 2.21, as to duty 4.3.

Table 42.—*Variations of the ratio $\frac{i_1-1}{i_3-1}$ in relation to discharge, width of channel, fineness of débris, and slope.*

		Values of $\frac{i_1-1}{i_3-1}$ for group—			
		1	2	3	4
$Q=$	0.093	2.6	....	....	....
	.182	3.9	1.4	....	....
	.363	....	2.4	1.8	1.7
	.545	....	....	2.7	....
	.734	....	4.1	3.1	3.0
	1.119	....	....	....	3.9
$w=$	0.44	5.5	....	....	....
	.66	1.9	3.9	....	....
	1.00	....	2.0	3.1	....
	1.32	....	1.5	2.4	....
	1.96	....	....	1.7	....
Grade	(A)	2.7	....	....	....
	(B)	1.9	3.6	....	....
	(C)	1.7	2.0	....	....
	(D)	....	1.6	....	....
	(G)	....	....	3.0	....
	(H)	....	....	2.4	....
S	.05	1.6	....	....	....
	1.0	2.9	1.9	....	....
	1.2	....	....	3.9	....
	2.0	....	5.5	....	....
	2.4	....	....	14.1	....

In Table 42 the values of $\frac{i_1-1}{i_3-1}$ correspond to those of $\frac{i_1}{i_3-1}$ in Table 41 and are similarly derived from data of Tables 27 to 40. The purpose of the table is to show how the dominance of control by slope, as expressed by a ratio, varies with certain conditions.

A comparison of tabulated values for the several ratios shows that the ratios associated with efficiency vary with conditions more rapidly than those associated with capacity, but less rapidly than those associated with duty. In Table 42, just as in Table 41, there are no exceptions as to the direction of the trend of variation.

Bearing in mind that the alphabetic order in which the grades are arranged is the order from fine to coarse, and that variation with respect to form ratio is the inverse of variation with respect to width, we see that the general fact shown by the table is that the dominance of control by slope—a dominance always pronounced—is notably increased by increase of slope, discharge, fineness, or form ratio.

$$\frac{i_1-1}{i_3-1}=f\,(\acute{S},\acute{Q},\acute{F},\acute{R})\text{ -------- }(74)$$

SUMMARY.

With débris of a particular size and a channel bed of a particular slope, there is a particular discharge which is barely competent to cause transportation. With increase of discharge above this barely competent discharge, there is a proportional addition to the stream's potential energy. The relation of capacity to discharge is formulated on the assumption that the capacity is proportional to some power of the added energy, and therefore to the same power of the added discharge. As each grade of débris is somewhat heterogeneous as to the size of its grains, this assumed principle can not be applied strictly; the practical assumption is that capacity varies with a power of the difference between the discharge and a constant discharge, the constant being so chosen as best to harmonize the data.

By means of such formulation the data were readjusted and the rate of variation of capacity with discharge, or the index of relative variation, i_3, has been computed for a variety of conditions. It is found to be greater as the slope of channel, the discharge, the fineness of débris, and the form ratio are less. The average of the values computed for laboratory conditions is 1.42 and the ordinary range is from 1.00 to 2.00.

The rate at which the efficiency of the stream and the duty of the stream's water vary with discharge is denoted by an index which is less by unity than that for capacity. Its average is 0.42 and its ordinary range is from 0 to 1.00.

It has previously been shown that the corresponding indexes showing the relation of capacity to slope are larger. In other words, capacity is more sensitive to changes of slope than to changes of discharge. If relative sensitiveness to the two controls be expressed by a ratio, the average value of that ratio is 1.36. The ratio varies with conditions, being relatively large when slope, discharge, fineness, and form ratio are relatively small.

The primary adjustment of observations of capacity, described in Chapter II, was an adjustment with respect to slope. The probable errors computed from differences between adjusted and unadjusted values were influenced by only a portion of the observational errors. In readjusting values of capacity with respect to discharge, another division of the observational errors was encountered and its importance was estimated. The probable errors computed from the results of the two adjustments are believed to represent with sufficient approximation the order of precision of the adjusted values of capacity, which constitute the main body of data for the discussions of the report. The order of precision is expressed by saying that the average probable error of the adjusted values is a little more than 3 per cent.

CHAPTER VI.—RELATION OF CAPACITY TO FINENESS OF DÉBRIS.

FORMULATION.

To study the laws affecting the control of capacity for traction by fineness of débris, capacities should be compared which are subject to like conditions in all other respects. For this purpose data from Table 12 were arranged as in Table 43, where the capacities in each horizontal line are conditioned by the same slope, discharge, and width of channel. All the data of that table pertain to a slope of 1.0 per cent; but similar tables were constructed for slopes of 0.5, 0.7, 1.4, and 2.0 per cent.

The same data were also plotted on logarithmic paper; and, after a preliminary examination, five sets were selected for special investigation. The plots of these appear in figure 50, where ordinates are logarithms of capacity and abscissas are logarithms of linear fineness. It is to be noted that the zero of log C is not the same for the different graphs. The graphs were moved up or down, so as to avoid confusion through intersection.

The first law illustrated by the plots is that capacity increases as fineness increases; the second, that it increases more rapidly for small fineness than for great fineness. Despite irregularities of the data it is evident that the locus of log $C=f$ (log F) is a curve, and that the function has a general resemblance to those found in comparing capacity with slope and discharge.

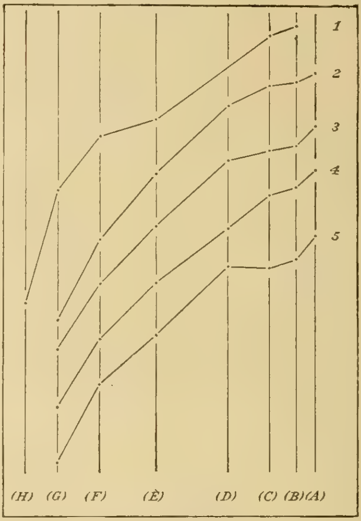

FIGURE 50.—Logarithmic plots of capacity for traction in relation to fineness of débris; corresponding to data in Table 44.

TABLE 43.—*Values of capacity for traction, arranged to illustrate the relation of capacity to grades of débris.*

Conditions.			Value of C for grade—							
S	w	Q	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
1.0	0.66	0.093		10.8	13.8	9.1				
		.182	39.5	33.5	32.1	29.8				
		.363		81	73		24.8	20.5	8.5	
		.545	140	120	112	101				
		.734			152		40	39	30.4	12.8
		1.119							49	25.2
	1.00	.093								
		.182	37.5	30.1	31.2	24.0	14.8			
		.363	100	85	85	73	33.8	14.0		
		.545		143	140	108				
		.734	231	199	180	153	72	42.8	26.9	
		1.119			276		138	79.5	61	
	1.32	.093								
		.182	36.8	29.3	21.4					
		.363	104	79	79	59.2	36.3			
		.545		140	129					
		.734	250	204	187	131	73	40.2	18.9	
		1.119					123	70	52.2	
	1.96	.093								
		.182								
		.363	96	67.6	60.0					
		.545		120	111					
		.734	240	190	190					
		1.119	359	313	343					

For any velocity, as determined by slope, discharge, and width, there is a competent fineness, marking the limit between traction and no traction; and to this extent, at least, the relation of fineness to traction is analogous to the relations of slope and discharge. It is not easy to carry the analogy further, because slope and discharge are conditions of active force, and fineness is a condition of reactive force, or resistance; but an experiment in formulation reveals a parallelism quite as striking as that between the capacity-slope and capacity-discharge functions.

Assuming

$$C=b_4\ (F-\phi)^p \qquad \text{(75)}$$

in which ϕ is a constant fineness and b_4 a constant of the numerical value of capacity when $F=\phi+1$,[1] the five sets of data in Table 44 were treated graphically for the determination of ϕ and p. The methods were such as have already been described (pp. 65 and 139). The formulas were then used to compute readjusted values of capacity, C_r, and values of the index of relative variation, i_4, and probable errors were also computed.

TABLE 44.—*Numerical data connected with the plots in figure 50, and illustrating the relation of capacity for traction to grades of débris.*

No. of plot in figure 50		1				2				3			
Conditions of experiments	w	0.66				1.00				1.00			
	Q	0.363				0.734				0.363			
	S	1.4				0.7				1.4			
Parameters of equations	ϕ	41				55				49			
	p	0.62				0.60				0.58			
	b_4	4.5				2.4				3.7			
Average probable errors	C	6.8				7.6				4.9			
	Cr	2.8				2.9				1.9			
		C	C_r	i_4	i_1	C	C_r	i_4	i_1	C	C_r	i_4	i_1
Data and computed results	Grade (A)					121	140	0.63	1.83	185	196	0.61	1.79
	Grade (B)	137	145	0.65	1.54	110	123	.64	1.66	149	173	.62	1.63
	Grade (C)	124	123	.67	1.55	106	102	.66	1.50	143	143	.63	1.53
	Grade (D)			.69		85	76	.70	1.72	127	108	.66	1.63
	Grade (E)	49.4	59	.81	2.10	40	42	.87	1.68	62	62	.80	1.78
	Grade (F)	41	37	1.08	1.99	20	21.7	1.42	2.35	33.4	34.4	1.18	2.42
	Grade (G)	23	22	1.82	2.71	8	7.4	5.45	4.11	16.3	16.3	2.80	3.15
	Grade (H)	6.9	7.1	13.50	4.69								

No. of plot in figure 50		4				5			
Conditions of experiments	w	1.32				1.32			
	Q	0.734				0.363			
	S	1.0				2.0			
Parameters of equations	ϕ	48				55			
	p	0.61				0.50			
	b_4	3.8				11.4			
Average probable errors	C	1.7				6.2			
	Cr	0.6				2.4			
		C	C_r	i_4	i_1	C	C_r	i_4	i_1
Data and computed results	Grade (A)	250	250	0.64	1.71	328	319	0.53	1.97
	Grade (B)	204	219	.65	1.71	255	285	.54	1.63
	Grade (C)	187	180	.66	1.47	233	242	.55	1.52
	Grade (D)	131	133	.70	1.85	237	190	.58	1.92
	Grade (E)	73	74	.84	1.54	112	115	.72	1.60
	Grade (F)	40.2	40.2	1.22	2.40	66	67	1.19	2.03
	Grade (G)	18.9	19	5.20	3.43	28.3	27.4	4.55	3.67
	Grade (H)								

PRECISION.

The average probable error of the readjusted capacities was found to be ±2.1 per cent. This error is to be ascribed in part to discordance of the data among themselves, and in part to discordance of the formula with the data; but the distribution of the residuals is not such as to imply important discordance of the formula.

---

[1] The dimensions of capacity are $M^{+1}T^{-1}$, and of fineness L^{-3}. The constant b_4, being equal to $C/(F-\phi)^p$, has dimensions $L^{+3p}M^{+1}T^{-1}$.

There are, however, important discordances among the data. Considered as errors, the discordances constitute a group which were not detected in the adjustments of capacities to slopes and to discharges, but which escaped those tests because related peculiarly to the grades of débris. From the residuals of the present readjustment the average probable error of capacities before readjustment is estimated at ±5.4 per cent, whereas the average probable error of the body of once-adjusted capacities from which these were selected was estimated at 2.5 per cent. On the assumption that the estimate for the whole body of values applies to the selected group, the share of error associated with the grades is estimated as $\sqrt{5.4^2-2.5^2}=\pm 4.8$ per cent.

Inspection of the logarithmic plots suggested that part of the discordance of the data is systematic. To bring out the systematic element the original values of capacity in Table 44 were divided by the readjusted values, and means were taken of the quotients. The means are listed below, and in figure 51 they are plotted logarithmically in relation to fineness. The plotted points conspicuously out of line are those for grades (B) and (D), the capacities determined for grade (B) being relatively too small and those for grade (D) too large. The same result was obtained from a canvass of a wide range of data.

Ratios of original values of capacity to adjusted values.

Grade	(A)	(B)	(C)	(D)	(E)	(F)	(G)
Linear fineness	1,002	812	602	388	178	95.9	43.4
Mean ratio	0.96	0.89	1.01	1.13	0.98	0.97	1.02

It is surmised that these errors arise in part from variations of experimental method, and this suspicion attaches especially to grade (B), which was the first to be treated in the laboratory. It attaches much less to grade (D), for which the experimental method was about the same as for grades (A), (E), and (F). So far as the quality of the experimental work is gaged by the probable error, that on grade (D) would appear to be considerably below the average.

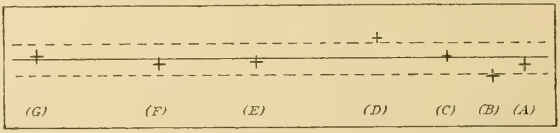

FIGURE 51.—Average departures of original values of capacity from the system of values readjusted in relation to fineness of débris. The horizontal line represents the readjusted system. The broken lines, above and below, correspond to departures of 10 per cent.

It is surmised that systematic error may also be connected with properties of the grades other than that of fineness. Range of fineness has already been appealed to as an explanation of apparent anomalies as to competent slope. From the experiments with mixtures (Chapter IX) we know that great range within a grade would tend to increase capacity for traction. As the range is small for grade (A), regularly increases to grade (E), and is again small from (F) to (H), the influence of this factor tends to enhance the capacity of grade (E); but the effect of that influence is not apparent in the diagram.

The separation of grades, being effected by sieves, was a gaging of grains by certain dimensions. The grains may have differed also as to shapes and densities, and each of these properties would affect capacity. The débris first obtained for the laboratory had been washed from the bed of Sacramento River when a flood broke the levee below the mouth of American River. This furnished material for the finer grades. Other lots of débris were taken from the bed of American River, and these furnished material chiefly for the coarser grades. So far as the separations from the different lots coincided, they were used indiscriminately. It is possible that grade (D) was composed chiefly of the coarser particles of a fine alluvium, while grade (E) was composed chiefly of the finer particles of a relatively coarse alluvium. As any natural body of tractional débris is the result of a sorting process in which tractionable particles are separated from the immovable on one side and from the suspendible on the other, it is likely to include among its coarser grains many which are tractionable only because of low density or favorable shape, and among its finer grains many which escape suspension because of high density or unfavorable shape.

Thus it appears possible that the superior mobility of grade (D) was determined by properties other than size. Unfortunately the record is not of such character that the value of this suggestion can now be tested.

A third suggestion pertains to the gaging of fineness. The method of gaging included a weighing and involved certain assumptions as to homogeneity in average density and in shape which may not have been fully warranted.

These various suggestions, while not susceptible of test at the present time, are sufficiently plausible to show the possibility of definite causes for the discordances discovered by the comparison of data from different grades. In my judgment it is proper to ascribe the greater discordances to such causes, and to view them as abnormalities with respect to the law connecting capacity with fineness.

In view of the magnitude of the abnormalties or discordances, it does not appear profitable to extend the readjustment of data to other and shorter sets. The five sets in Table 44 were selected because they included great range in fineness, and because they were qualified to yield fairly definite values of the constant ϕ.

VARIATIONS OF THE CONSTANT ϕ.

The laws which control the variation of ϕ have not been developed from the observations, but their general character may be inferred deductively by considering the relations of competent fineness to various conditions—it being assumed that ϕ is intimately related to competent fineness. Postulate a current of which the velocity is determined by a particular slope, a particular discharge, and a particular width. For this current a certain fineness is competent. Increase of slope or discharge increases the velocity and makes a lower fineness competent. Decrease of width, which corresponds to increase of form ratio, increases velocity and makes a lower fineness competent. Thus competent fineness, and therefore ϕ, varies inversely with the slope, discharge, and form ratio.

$$\phi = f\,(\grave{S}, \grave{Q}, \grave{R}) \text{ ....} (76)$$

INDEX OF RELATIVE VARIATION.

Framing an equation of the type of (33)—

$$C = v_4 F^{i_4} \text{ ....} (77)$$

in which i_4 is the index of relative variation for capacity and fineness. The formula for the index (cf. pp. 100 and 141) is

$$i_4 = \frac{pF}{F-\phi} \text{ ....} (78)$$

With this formula, values of i_4 were computed from the data in Table 44, and they are given in the lower part of that table.

By inspection it appears that the index increases as fineness diminishes, its growth being at first slow but becoming rapid as competent fineness is approached. Because of the discordances of the data it is not easy to derive a body of values of the index for discussion in relation to other conditions, but it is relatively easy to obtain comparative values of the synthetic index, I_4, and the variations of these values may be assumed to show the same trends as the variations of i_4. Values of I_4 were computed between corresponding data of grades (C) and (G) by the formula

$$I_4 = \frac{\log C_{\text{I}} - \log C_{\text{II}}}{\log F_{\text{I}} - \log F_{\text{II}}}$$

in which C_{I} and C_{II} are specific capacities corresponding to the finenesses F_{I} and F_{II}; and the results are given in Table 45.

From these results it is inferred (1) that the index varies inversely with the slope, (2) that it varies inversely with discharge, and (3) that it varies directly with width, and therefore inversely with form ratio. The response is in general of a very pronounced character, but to this there is exception in one of the comparisons with width. It is possible that the index is a maximum function of width and a minimum function of form ratio. With some reservation on this point, we may generalize:

$$i_4 = f\,(\grave{S}, \grave{Q}, \acute{F}, \grave{R}) \text{ ....} (79)$$

If equation (79) be compared with equations (39) and (68), it will be seen that the variation of the capacity-fineness index observes the same laws of trend as the variations of the capacity-slope index and the capacity-discharge index. In view of this general parallelism of variation, it is thought that the relative magnitudes of average i_4, average i_1, and average i_3 may be adequately discussed by means of a moderate number of comparisons. Accordingly only those values of i_4 computed from the five equations of Table 44 are used. The corresponding values of i_3 are not available, but those of i_1

are given in Table 15. They have been copied into Table 45, so as to be conveniently compared.

Inspection shows that i_4 is in general much smaller than i_1 but that it becomes greater as the limit of competence is approached. As to the first of these generalizations there can no question, but the second is not equally satisfactory. In the vicinity of competence the value of i_4 is highly sensitive to the influence of ϕ; and in the same region i_1 is highly sensitive to σ. The features of the table might be produced by slight overestimates of ϕ or by slight underestimates of σ. In view of this consideration it is probably best to leave the higher values of the index out of the account and base a computation of averages wholly on the lower values. Including only the 28 values of each index associated with grades (A) to (F), the means are, for i_4 0.77, for i_1 1.79; and the ratio of the second to the first is 2.4; that is, the sensitiveness of capacity to control by slope is estimated to be 2.4 times as great as its sensitiveness to control by fineness. The ratio of sensitiveness for slope and discharge i_1/i_3 having been estimated at 1.36, it follows that the ratio for discharge and fineness is $\frac{2.4}{1.36}=1.8$.

$$\text{Mean } i_1 : \text{mean } i_3 : \text{mean } i_4 : : 2.4 : 1.8 : 1.0.$$

It is to be understood that these estimates are of the most general character. The ratios doubtless vary notably with conditions.

The property with which capacity has been compared in this chapter is linear fineness, F, defined as the reciprocal of diameter, or as the number of grains to the linear foot. Bulk fineness, F_2, defined as the reciprocal of volume, is proportional to the cube of linear fineness. It follows that the index of relative variation when capacity is compared with bulk fineness is one-third the corresponding index, i_4, for capacity and linear fineness; and the same factor applies to synthetic indexes. If bulk fineness were substituted for linear fineness in equations of the form of (75), the values of ϕ would be quite different and the values of p would be uniformly one-third as great.

TABLE 45.—*Values of I_4, the synthetic index of relative variation for capacity and fineness, compared with slope, discharge, and width of channel.*

Fixed conditions	Coarser grade	(G)		(G)		(G)		(G)		(G)		(G)	
	Finer grade	(C)		(C)		(C)		(C)		(C)		(C)	
	Slope (per cent)					1.8		2.0		2.0		2.0	
	Discharge (ft.^{3}/sec.)	0.363		0.734						0.363		0.734	
	Width (feet)	1.32		1.32		1.32		1.32					
Variables compared		S	I_4	S	I_4	Q	I_4	Q	I_4	w	I_4	w	I_4
		1.8	1.05	1.0	0.99	0.363	1.05	0.363	0.92	0.66	0.59		
		2.4	.76	2.0	.61	.734	.65	.734	.61	1.00	.74	1.00	0.57
										1.32	.92	1.32	.61

DUTY AND EFFICIENCY.

The relations of duty and efficiency to capacity involve discharge and slope but are independent of fineness. Fineness, therefore, has exactly the same control of duty and efficiency that it has of capacity, and the conclusions of this chapter apply without qualification to duty and efficiency.

SUMMARY.

Capacity for traction is greater for fine débris than for coarse—that is, capacity increases with fineness. The law of increase admits of formulation in a manner strictly analogous to that employed in comparing capacity with slope and discharge—that is, it is found that capacity varies approximately with a power of the fineness less a constant fineness. The value of the constant fineness varies with conditions, being greater as slope, discharge, and form ratio are greater. The rate at which capacity varies with change of fineness, or the index of relative variation, is not the same for all conditions, being greater as slope, discharge and form ratio are less. Under similar conditions the rate is less than the corresponding rate for capacity and slope, the average ratio between them being as 1 to 2.4.

The arrangement of capacities in accordance with the assumed law of increase develops discrepancies which are believed to be of the nature of systematic errors. The largest of these have a magnitude of about 10 per cent. They are tentatively ascribed to peculiarities of the débris used in experiments and to imperfectly developed laboratory methods.

CHAPTER VII.—RELATION OF CAPACITY TO VELOCITY.

PRELIMINARY CONSIDERATIONS.

The work of stream traction is accomplished by the movement of water along the bed of the channel. For that reason the system of water movements and water velocities near the bed is intimately related to the load or capacity for load. In certain parts of this paper and in the writings of some other investigators use is made of the term "bed velocity," or its equivalent, but the term has no satisfactory definition. The difficulties which are encountered in this connection have to do also with the vertical velocity curve.

In all the streams with which we are here concerned the flow is eddying or turbulent. At any point the direction of motion and the velocity are constantly changing. If a mean be taken of the instantaneous forward components of velocity—the components parallel to the axis of the stream—it gives for the point a mean velocity coordinate with the mean velocity for the cross section obtained by dividing the discharge by the sectional area. It will be observed that the mean at a point is a mean with respect to time, while the sectional mean is primarily a mean with respect to space. The mean at a point, as thus defined, being called V_p, the vertical velocity curve may be defined as the curve obtained by plotting the values of V_p for any vertical of the current in their relation to depth. As commonly drawn by hydraulic engineers, it terminates downward at some distance from the origin of velocities, OD—say at B in figure 52—connoting a finite velocity for the water in actual contact with the bed. This implication contravenes a theorem of hydrodynamics that the velocity at contact with the wall of a conduit is either zero or indefinitely small. The theorem is believed to have been established experimentally by the work of J. L. M. Poiseuille[1] and is generally accepted. In the direct study of the velocities of streams instrumental observation is not carried from surface to bed, but ceases at some point, C, and the drawing of the curve below that point is a matter of inference. The inference accordant with the hydrodynamic principle is that the curve changes its course below C and reaches the origin at or near O.[2] This inference accords also with our observations in connection with the study of saltation (see p. 29); and those observations suggest likewise that the curve is materially modified by the resistances to the current involved in the work of saltation.

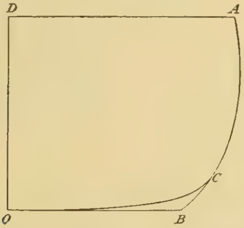

FIGURE 52.—Vertical velocity curve, drawn to illustrate its theoretic character near the stream's bed. OD is the origin of velocities.

It thus appears that in the region with which traction studies are specially concerned the range of V_p is great. The work of traction depends on a system of velocities and not on a single one, and there is no individual value of V_p with special claim to the title "bed velocity." It would be possible to define bed velocity as the value of V_p at some particular distance from the bed or at a distance constituting some particular fraction of the depth of current; but such a definition would be hard to apply.

However smooth a stream bed of débris may be in its general aspect, it is never smooth as regards details. Figure 53 gives an ideal profile, the intersection of a bed by a vertical plane. Not only are there salients and reentrants, but some of the reentrants communicate with the voids within the mass of débris. In many of

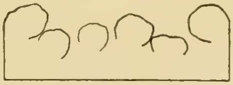

FIGURE 53.—Ideal profile of a stream bed composed of débris grains.

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[1] See Lamb's Hydrodynamics, 3d ed., p. 544, 1906.

[2] See Cunningham, Allan, Hydraulic experiments at Roorkee, p. 46, 1875, and Inst. Civil Eng. Proc., vol. 71, p. 23, 1882, where he discusses the horizontal velocity curve; and Von Wagner, idem, p. 90.

the reentrants are doubtless stationary eddies, with reversed currents where the value of V_p is negative. It appears equally difficult to give definition to the bed as a datum from which to measure upward, and to select and define a locus for bed velocity. There is reason to suspect also that the problem as thus stated is unduly simplified by the assumption that the bed is a stable entity, clearly separate from the zone of saltation above. It did indeed so appear when the process of saltation was studied through the glass wall of the observation trough, but what was witnessed was the phase of the process at the edge of the channel bed, where the current was retarded by the resistance of the channel wall. At a distance from that wall, in the region where the cloud of saltatory particles effectually precludes visual observation, the passage from stability to mobility may be less definite. I am led to this suggestion by the observations, quoted by McMath,[1] of a civil engineer who descended in a diving bell to the bottom of the Mississippi at a point where the depth was 65 feet and the bottom of sand. Stepping to the bed, he sank into it about 3 feet, and then thrusting his arm into the yielding mass, could feel its flowing motion to a depth of 2 feet, the velocity diminished downward. In interpreting these phenomena, allowance must be made for the fact that the presence of the diving bell created an abnormal condition and if it rested on the bed put a stop to saltation. The flow of the sand is then to be ascribed to the difference in water pressure on the two sides of the bell. But the fact of the flow seems to indicate an antecedent state of mobility, a layer of the bed being supersaturated so as to have the properties of quicksand. If such a layer exists, then the transition from the bed to the saltation zone is not abrupt but gradual.

The difficulties in attempting to define bed velocity are supplemented by those which affect the measurement of velocities near the bed while traction is in progress (p. 26), and together they have served to prevent the use of bed velocity as a factor for quantitative comparison with capacity. This result has been regretted because the forces which accomplish traction are applied directly through the velocities of water near the bed, and it was admitted only after the failure of repeated attempts to obtain serviceable estimates of bed velocity.

In the present chapter observed or interpolated capacities are compared with mean velocities of the stream, mean velocity being computed as the quotient of measured discharge by measured sectional area. The measurements of discharge and width being relatively simple and accurate, the determinations of mean velocity have the same degree of precision as the measurements of depth. (See p. 26.)

In comparing capacity with mean velocity, it is convenient always to treat fineness of débris and width of channel as constants, but it is also advantageous to recognize three separate points of view as to the status of discharge, slope, and depth.

First, we may treat discharge as constant, in which case slope and depth vary, along with velocity and capacity. Each of the observational series (Tables 4, 12, and 14) conforms to this viewpoint. When discharge is constant, the increase of power necessary to increase velocity is given by increase of slope, and the increase of velocity causes the unchanged discharge to occupy less space. As velocity and capacity increase, slope increases and depth decreases.

Second, we may treat slope as constant. With slope constant, the increase of power necessary to increase velocity is given by increase of discharge, but the rate at which discharge is increased is greater than the rate of increase given to velocity, and the increased discharge therefore requires more space. As velocity and capacity increase, both discharge and depth also increase.

Third, we may treat depth as constant. To increase velocity by increasing slope will, as we have seen, reduce depth. To increase velocity by increasing discharge will, as we have seen, increase depth. To increase velocity without changing depth, it is necessary to enlarge both slope and discharge. No experiments were conducted with fixed depths, but the data for this comparison are readily obtained by interpolation.

It is proposed to examine the relation of capacity to velocity from each of these viewpoints, developing the results so far as necessary to give a basis for a comparison of the viewpoints.

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[1] McMath, R. E., Van Nostrand's Mag., vol. 20, p. 227, 1879.

A preliminary remark applies to all. For each grade of débris and width of channel, and for each specific assumption of a constant discharge, slope, or depth, there is necessarily a competent mean velocity, below which no traction takes place. The conception of such a competent velocity has underlain all the discussions of competent slope, competent discharge, competent fineness, and competent form ratio. A broad analogy therefore points to the propriety of formulating the capacity-velocity relation as other relations of capacity have been formulated. And the inference from analogy finds support in logarithmic plots of $C=f(V_m)$ under each of the three above-mentioned conditions. It may fairly be assumed, therefore, that the index of relative variation for capacity and velocity itself varies with velocity, being relatively small for high velocities, being relatively large for low velocities, and becoming indefinitely large as competent velocity is approached.

For the purposes of this chapter, however, it has seemed best to employ a simpler method, using only the synthetic index of relative variation—characterized by the symbol I. Calling the synthetic index for the variation of capacity with respect to mean velocity I_V, we may conveniently distinguish by I_{VQ}, I_{VS}, and I_{Vd} the values associated severally with the special cases of constant discharge, constant slope, and constant depth.

The computations of the index are made chiefly by the formula

$$I_V=\frac{\log C'-\log C''}{\log V_m'-\log V_m''} \text{ - - - - - - - (80)}$$

in which C' and C'' are specific capacities, and V_m' and V_m'' are the corresponding mean velocities. Graphically, I_V is the inclination of a line connecting two points of which the coordinates are, for the first, log C' and log V_m', and for the second, log C'' and log V_m''. Where the available data serve to place more than two points on the logarithmic plot of $C=f(V_m)$, definite suggestion may thereby be made that the line connecting the extreme points does not constitute the most probable location of the chord theoretically corresponding to I_V; and in such cases a line is drawn with regard to all the data, and its inclination is measured on the plot.

The subject of competent velocity, which is of interest independently of the formulation of capacity and velocity, will be considered at the end of the chapter.

THE SYNTHETIC INDEX WHEN DISCHARGE IS CONSTANT.

In Table 14 are 73 series of values of V_m, each value corresponding to a stated value of S. The coordinate series in Table 12 contain values of C corresponding to the same values of S. From each pair of series were taken the highest and lowest values of V_m and the corresponding values of C, and from these four quantities was computed a value of I_{VQ}. The 73 values of the index are shown in Table 46, where the arrangement is such as to exhibit the variation of the values with respect to discharge.

Table 46.—*Values of I_{VQ}, the synthetic index of relative variation for capacity in relation to mean velocity, when discharge is constant.*

Grade.	w	Value of I_{VQ} when discharge (in ft.^{3}/sec.) is—					
		0.093	0.182	0.363	0.545	0.734	1.119
(A)	1.32	....	....	4.05	....	3.62	....
	1.96	....	....	3.55	....	3.22	2.38
(B)	.23	5.45	4.50	....	....	....	....
	.44	4.32	4.45	....	....	....	....
	.66	5.76	4.61	2.93	4.22	....	....
	1.00	....	5.68	5.37	....	5.15	....
	1.32	....	2.92	....	2.48	2.51	....
	1.96	....	....	4.59	3.43	3.38	3.49
(C)	.44	6.31	4.30	....	....	....	....
	.66	3.36	3.29	2.82	3.04	2.92	....
	1.00	....	3.63	3.56	2.52	3.11	....
	1.32	....	2.54	3.90	3.27	3.69	....
	1.96	....	....	4.36	3.74	3.69	3.89
(D)	.66	5.38	4.30	....	4.59	....	....
	1.00	....	4.16	4.13	4.34	3.94	....
	1.32	....	....	5.34	....	3.34	....
(E)	.66	....	....	5.98	....	6.00	....
	1.00	....	5.10	5.35	....	3.43	....
(F)	.66	....	7.50	6.67	....	....	....
	1.00	....	11.46	9.63	....	....	....
	1.32	....	....	8.41	....	....	....
(G)	.66	....	....	9.22	....	8.30	10.60
	1.00	....	....	8.80	....	8.49	8.05
	1.32	....	....	13.60	....	10.67	8.26
(H)	.66	....	....	12.57	....	8.97	8.49

The values which lie in any horizontal line agree as to all conditions except discharge. On comparing the columns for discharges 0.093 and 0.182 ft.^{3}/sec., it is seen there are six lines carrying values in both columns. The means of these values are 4.80 and 4.21, the greater mean belonging with the smaller discharge. In the column for discharge 0.182 are nine values coordinate with values in the column for discharge 0.363, and the means for the two groups of nine are 5.31 and 5.04. Again the greater mean is associated with the smaller discharge, and the same relation is found by other combinations. The partial means resulting from these reductions are arranged in the upper division of Table 47. The general fact exhibited is that the index, other conditions being the same, varies inversely with discharge.

The same method was employed to discover the nature of the control of the index, first, by grade of débris and, second, by width of channel; and the partial means are grouped in the middle and lower divisions of Table 47. Of the eight pairs of means connected with grade, seven agree in testifying that the index varies inversely with fineness. The exceptional testimony comes from the comparison of grades (B) and (C); and although it is emphatic, it serves rather to illustrate the general discordance of data from the experiments with grade (B) than to qualify the general law as to the index.

Table 47.—*Partial means based on Table 46, illustrating the control of I_{VQ}, by discharge, fineness, and width.*

Number of values.	Means of I_{VQ} for discharge (ft.³/sec.) of—					
	0.093	0.182	0.363	0.545	0.734	1.119
6	4.80	4.21				
9		5.31	5.04			
7			3.90	3.51		
16			6.58		5.47	
8					5.81	5.64

Number of values.	Means of I_{VQ} for grade—							
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
4	3.45	3.49						
6		4.01	3.79					
9			3.34	4.39				
5			3.21		5.17			
5			3.44			8.73		
4					5.19		8.71	
3						8.24	10.54	
3							9.39	10.01

Number of values.	Means of I_{VQ} for width (feet) of—					
	0.23	0.44	0.66	1.00	1.32	1.96
2	4.97	4.38				
4		4.84	3.80			
15			5.59	5.84		
12				5.56	5.87	
7					3.36	3.62

Of the five pairs of means connected with width, three show increase of the index with increase of width and two give the opposite indication. The contrasts are not strong in any case, and the nature of the law is not clear. It may be that the normal variation with width is so slight as to be masked by accidental errors of the data; or it may be that the index, like the constant σ, is a minimum function of form ratio.

By dividing the slope interval covered by a computed value of the index and computing separately the indexes for the two subintervals, it was found that the index associated with the higher slopes has a smaller value than that for the lower slopes—that is, the index varies inversely with slopes.

To compare the control of capacity by mean velocity with its control by slope the 73 values of I_w (the synthetic index of relative variation of capacity and slope, under condition of constant width) corresponding to the tabulated values of I_{VQ} were computed. Each value of I_{VQ} is greater than the corresponding value of I_w, the ratio ranging from 1.4 to 4.0. The mean of 73 values of I_{VQ} is 5.33; the mean I_w is 2.05; and the ratio of the means is 2.60. It is in general true that the greater the indexes the greater the ratio between them.

In Table 48 means of the two indexes are shown for the several grades of débris. Each index varies with fineness and so, too, does the ratio of indexes.

Table 48.—*Synthetic indexes, comparing the control of capacity by mean velocity with the control by slope, and comparing both controls with grades of débris.*

Grade.	Number of separate determinations.	Mean I_{VQ}	Mean I_w	$\frac{\text{Mean } I_{VQ}}{\text{Mean } I_w}$	$\frac{\text{Mean } I_w}{\text{Mean } I_{VQ}}$
(A)	5	3.62	1.87	1.93	0.52
(B)	18	4.35	1.94	2.24	.45
(C)	19	3.57	1.85	1.93	.52
(D)	9	4.50	1.87	2.41	.42
(E)	5	5.17	1.83	2.83	.35
(F)	5	8.73	2.27	3.84	.26
(G)	9	9.56	2.60	3.68	.27
(H)	3	10.01	3.20	3.12	.32
	73	5.33	2.05	2.60	.38

MEAN VELOCITY VERSUS SLOPE.

The comparison of I_{VQ} with I_w affords, incidentally, an estimate of the relative variation of mean velocity and slope. The rate of variation of capacity with mean velocity being I_{VQ}, the rate of variation of mean velocity with capacity is $1/I_{VQ}$; and the rate of variation of capacity with slope being I_w, the rate of variation of mean velocity with slope is

$1/I_{VQ} \times I_w = I_w/I_{VQ}$. The values of I_w/I_{VQ} listed in Table 48 are therefore estimates of the relative variation of mean velocity in relation to slope, and they have the same quality as the corresponding values of I_w and I_{VQ}. They are subject to the limiting conditions of constant discharge, fineness, and width, and they are averages of variability for practically the entire range of conditions realized in the laboratory, with the exception of those in the immediate neighborhood of competence. For this range of conditions mean velocity varies, on the average, as the 0.38 power of the slope.

This result is comparable with the generalization embodied in the Chezy formula, which makes mean velocity vary with the 0.5 power of the slope. The two are not inconsistent because they pertain severally to loaded and loadless streams. In a loaded stream increase of slope augments load and thus develops rapidly a factor of resistance from which the loadless stream is free. Velocity, being limited by resistances, develops less rapidly when the conditions are such that the resistances develop more rapidly.

THE SYNTHETIC INDEX WHEN SLOPE IS CONSTANT.

For a selected slope, values of V_m may be found in Table 14 which agree as to width of channel and grade of débris and differ only as to the discharges with which they are associated; and in Table 12 may be found the corresponding values of capacity. Such pairs of values, when occurring in series of two to five, constitute data for the computation of values of I_{VS}. To cover the entire range of tabulated data without needless repetition choice was made of slopes 0.6, 1.0, 1.4, and 2.0 per cent. The data associated with these slopes gave 66 values of the index, the values being essentially independent except in a few instances. They are shown in Table 49. From them were derived the sets of partial means arranged in Table 50, the method of derivation being that described in connection with Table 47.

The means show that I_{VS} varies inversely with slope, the variation being of moderate amount. They leave little question that it varies inversely with fineness, though the evidence is somewhat conflicting. They indicate also a direct variation with trough width, the opposite tendency being indicated only by the means for the greatest widths. The plots of the data, not here reproduced, show that the index varies inversely with discharge.

TABLE 49.—*Values of I_{VS}, the synthetic index of relative variation for capacity in relation to mean velocity, when slope is constant.*

Grade.	S	Value of I_{VS} for width (feet) of—					
		0.23	0.44	0.66	1.00	1.32	1.96
(A)	.06	......	......	......	......	2.18	1.87
(B)	.6	......	......	3.82	4.60	3.24	5.15
	1.0	2.42	2.60	4.39	4.10	3.40	4.62
	1.4	3.30	......	3.80	4.45	3.24	......
	2.0	......	......	4.95	4.17	......	......
(C)	.6	......	4.38	3.20	3.31	4.20	2.80
	1.0	......	2.83	2.98	3.01	3.48	2.45
	1.4	......	2.89	2.34	3.35	3.10	2.03
	2.0	......	......	1.59	......	......	1.33
(D)	.6	......	......	3.55	2.55	4.10	......
	1.0	......	......	3.40	2.49	......	......
	2.0	......	......	2.72	2.85	......	......
(E)	.6	......	......	......	3.38	......	......
	1.0	......	......	3.68	3.06	2.39	......
	1.4	......	......	2.29	2.85	......	......
	2.0	......	......	......	2.79	......	......
(F)	1.0	......	......	2.21	2.94	......	......
	1.4	......	......	4.86	5.80	......	......
	2.0	......	......	4.92	4.72	......	......
	1.0	......	......	3.97	4.62	6.50	......
	1.4	......	......	3.63	4.92	2.06	......
	2.0	......	......	3.50	3.10	5.05	......
	1.4	......	......	9.78	......	......	......
	2.0	......	......	5.84	......	......	......

TABLE 50.—*Partial means based on Table 49, illustrating the control of I_{VS} by slope, fineness, and width.*

Number of values.	Means of I_{SV} for slope (per cent) of—			
	0.6	1.0	1.4	2.0
12	3.68	3.35	......	......
16	......	3.63	3.43	......
11	......	......	4.23	3.81

Number of values.	Means of I_{VS} for grade—							
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
2	2.02	4.19	......	......	......	......	......	......
13	......	3.81	2.87	......	......	......	......	......
6	......	......	30.5	3.13	......	......	......	......
4	......	......	......	2.82	3.23	......	......	......
5	......	......	......	......	2.93	4.11	4.05	......
2	......	......	......	......	......	......	3.56	7.81

Number of values.	Means of I_{VS} for width (feet) of—					
	0.23	0.44	0.66	1.00	1.32	1.96
1	2.42	2.60	......	......	......	......
4	......	3.17	3.23	3.47	3.54	2.97
18	......	......	3.57	3.72	......	......
11	......	......	......	3.46	3.71	......
6	......	......	......	......	3.27	3.15

THE SYNTHETIC INDEX WHEN DEPTH IS CONSTANT.

The capacities and mean velocities corresponding to particular depths were derived from the computation sheets described on page 95. The selected depths were 0.10, 0.14, 0.20, and 0.28 foot, and the data available for these depths afforded 32 values of the synthetic index, I_{Vd}. These are recorded in Table 51, and partial means derived from them are arranged in Table 52 so as to show variation in relation to fineness of débris and width of channel.

Table 51.—*Values of I_{Vd}, the synthetic index of relative variation for capacity in relation to mean velocity, when depth of current is constant.*

Width (feet).	Depth (feet).	Value of I_{Vd} for grade—					
		(A)	(B)	(C)	(D)	(E)	(G)
0.44	0.14	....	....	3.73	....	....	....
.66	.10	....	....	2.59	....	....	....
	.14	....	4.12	3.16	....	....	....
	.20	....	3.51	3.39	....	....	....
	.28	....	....	2.62	....	....	....
1.00	.14	....	....	3.59	3.17	....	....
	.20	....	4.02	2.80	3.51	4.46	....
	.28	....	....	3.44	....	....	7.86
1.32	.10	....	3.05	3.86	....	....	....
	.14	3.23	2.17	3.10	3.52	....	....
	.20	3.65	2.03	....	....	....	7.22
1.96	.10	....	3.92	3.02	....	....	....
	.14	2.36	3.41	3.60	....	....	....
	.20	2.23	4.50	4.27	....	....	....

Table 52.—*Partial means based on Table 51, illustrating the control of I_{Vd}, by fineness and width.*

Number of values.	Means of I_{Vd} for grade—					
	(A)	(B)	(C)	(D)	(E)	(G)
4	2.87	3.03	....	....	....	....
8	....	3.59	3.40	....	....	....
3	....	....	3.16	3.40	....	....
1	....	....	3.44	....	4.46	....
2	....	3.04	....	....	....	7.54
	Means of I_{Vd} for width (feet) of—					
	0.44	0.66	1.00	1.32	1.96	
1	3.73	....	3.28	....	....	
4	....	3.17	3.46	....	....	
3	....	....	3.71	2.88	....	
7	....	....	....	3.00	3.09	

With a single exception in each group of means, the indication is that the index varies inversely with fineness and directly with width. Under the condition of constant depth each change in mean velocity is accompanied by changes of both slope and discharge, and the influences of the two can not be examined separately. The features of the logarithmic plots, not here reproduced, show that the index varies inversely with slope and discharge, considered together.

THE THREE INDEXES.

In bringing together the results outlined in the preceding paragraphs we may replace width of channel by form ratio, bearing in mind that the two factors are so related that their variations are in opposite senses. So far as qualitative statement is concerned, the three synthetic indexes are identical in properties. The sensitiveness of capacity for traction to the control of mean velocity of current varies inversely with slope of channel, discharge, fineness of débris, and form ratio.

$$I_5 = f(\grave{S}, \grave{Q}, \grave{F}, \grave{R}) \quad \text{........} (81)$$

As to the first three conditions the generalization is unqualified, but it is possible that the function as to form ratio is of the minimum class instead of inverse.

The three indexes are not of the same magnitude. In comparing them I_{Vd} was made the standard, partly because the values computed for it are fewer. To compare with each of its 32 values, that value of I_{VS} which most nearly represents the same group of conditions was selected, and also a pair of values of I_{VQ} which collectively represent nearly the same conditions. Means were then derived for each index for each of the six grades to which they pertain, and also general means—all of which are shown in Table 53. In the same table are the ratios between general means and also between the corresponding grade means. For the general means I_{VQ} is 7 per cent greater than I_{Vd}, and I_{VQ} is the greater for all the partial means but one. For all the partial means but one I_{VS} is smaller than I_{Vd}, and for the general means it is 9 per cent smaller. Capacity is most sensitive to the mean velocity conditioned by constant discharge and least sensitive to the mean velocity conditioned by constant slope.

These results have a theoretic connection with the fact that capacity is more sensitive to changes of slope than to those of discharge. When discharge is constant the changes of velocity are caused by changes of slope, and the changes in capacity are those due to the changes of slope. When slope is constant the changes of velocity are caused by changes of discharge, and the changes in capacity are those due to changes of discharge. When depth is constant the changes of velocity are caused by concurrent changes of slope and discharge, and the changes in capacity are intermediate between those caused by slope alone and by discharge alone.

TABLE 53.—*Comparison of synthetic indexes of relative variation for capacity and mean velocity, under the several conditions of constant discharge, constant depth, and constant slope.*

Grade.	Number of comparisons.	Means.			Ratios.	
		I_{VQ}	I_{Vd}	I_{VS}	$\frac{I_{VQ}}{I_{Vd}}$	$\frac{I_{VS}}{I_{Vd}}$
(A)	4	3.34	2.87	1.97	1.16	0.69
(B)	9	3.55	3.41	4.19	1.04	1.23
(C)	13	3.60	3.55	2.96	1.01	.83
(D)	3	4.14	3.40	2.63	1.22	.77
(E)	1	4.39	4.46	3.06	.99	.69
(G)	2	8.84	7.54	3.86	1.17	.51
General means....		3.98	3.68	3.21	1.07	.91

It is profitable to consider the same facts also in relation to depth of current. Postulate an initial status, with a particular discharge and slope, determining a certain velocity, depth, and capacity. First, increase the slope until the velocity is doubled. The capacity is increased, let us say (borrowing mean I_{VQ} from the table) to 15.8 times its initial amount. At the same time the depth is reduced one-half. Second, after returning to the initial status, increase slope and discharge by such amounts as to double the velocity without changing the depth. The capacity grows (mean I_{Vd}) to 12.8 times its original amount. Third, starting from the initial condition as before, increase the discharge until velocity is doubled. The capacity grows (mean I_{VS}) to 9.2 times its original amount; and the depth is at the same time increased, being more than doubled. Thus, for the same (doubled) mean velocity, the capacity is greater as the depth is smaller. Mean velocity is more efficient for traction as depth is less.

Now, the primary direct cause of stream traction is bed velocity. A concurrent cause theoretically exists in the component of gravity parallel to the slope, acting directly on the load, but for all ordinary stream slopes this factor is negligible. Slope and discharge are (essentially) indirect causes and are causes only in so far as they occasion bed velocity. They also determine mean velocity, and, from one point of view, mean velocity may be said to control capacity by controlling bed velocity.

Let us assume, for the moment, that bed velocity determines capacity irrespectively of depth. Then the variations of capacity above described imply corresponding variations of bed velocity, and, as the mean velocity does not change, we may infer that the ratio of bed velocity to mean velocity is a function—a decreasing function—of depth.

This proposition is, to say the least, worthy of consideration, but it fails of demonstration because the assumption which paved the way for it is not valid. It is not true that the relation of capacity to bed velocity is independent of depth. In the first place, change of depth, when not accompanied by change of mean velocity, causes change in the mode of traction. Within the range of the above hypothetic conditions may occur both the dune rhythm and the antidune rhythm; and at least one of these has an influence on capacity. Moreover, these rhythms involve diversity of velocity from point to point along the bed, so that "bed velocity" has not a simple definition.

In the second place, the load, or the work of traction, reacts on the vertical distribution of velocities. In figure 54 the line *ABC* is assumed as the vertical velocity curve of a stream flowing in a straight conduit and bearing no load. *A′B′C*, identical except as to vertical dimensions, is assumed as the curve corresponding to the same mean velocity in a current one-half as deep. Introducing, now, the condition of traction, we may represent the upper limit of the zone of saltation by the line *DE*. The potential velocities within the zone are evidently quite different for the two depths of current, and they give advantage, for traction, to the shallower current. The work of saltation tends to retard the lower filaments of current and through these the higher filaments, reduc-

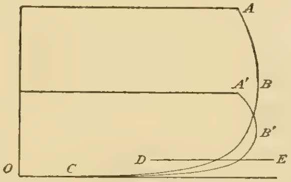

FIGURE 54.—Ideal curves of velocity in relation to depth, illustrating their relation to the zone of saltation. *O*=zero of velocity (horizontal) and of distance from the bottom (vertical).

ing the mean velocity and increasing the depth. If mean velocity and depth be restored by suitable changes in slope and discharge, a new and different vertical velocity curve will be obtained for each depth. While I am not able to deduce the exact nature of the changes, it seems clear that those portions of the new curves within the zone of saltation will be contrasted in some such way as are the potential curves of the drawing, and that for purposes of traction the advantage will still be with the shallow current. Provided the portions of the velocity curves within the zone of saltation show steeper gradient for the current of less depth, tractional capacity will for that current bear a higher ratio to mean velocity.

RELATIVE SENSITIVENESS TO CONTROLS.

The synthetic index of relative variation for capacity in relation to mean velocity, when the limiting condition is constant discharge, namely, I_{VQ}, has been estimated (p. 158) as 2.60 times the corresponding index, I_w for capacity in relation to slope. The same index has been estimated (Table 53) as 1.07 times I_{Vd} and 1.19 times I_{VS}. Combination of ratios indicates that I_{Vd} is 2.43 times and I_{VS} 2.18 times as great as I_w. While these figures have an appearance of exactitude, their order of precision is really low. They are built on averages of individual values of indexes, which among themselves are highly diversified. At best they represent the average of values covered by the range of experiments in the laboratory, but in part they are based on values covering much narrower ranges. Moreover, it was not possible, except in the case of I_{VQ} and I_w, to derive the compared series of values of the index from data representing exactly the same conditions. For these reasons the numerical results should be accepted only as indicating an order of sequence and an order of magnitude. The quantitative response of capacity to the change of mean velocity is much larger than its response to change of slope, probably more than twice as large. Minor differences depend on the conditions under which mean velocity varies. The response is greatest when velocities are subject to the condition of constant discharge, less when the restrictive condition is constant depth, and least when it is constant slope.

COMPETENT VELOCITY.

The demonstrations by Leslie, Hopkins, Airy, and Law of the proposition that the diameter of the largest particle a current can move is proportional to the square of the velocity involve the principle that the pressure of a current is proportional to the square of its velocity, and also the assumption that the forward pressures on different parts of the particle are the same, so that the total pressure is proportional to the sectional area of the particle.[1] Under that assumption the total pressure may be conceived as applied to the center of gravity of the particle, a consideration of importance when the motion given to the particle is of the nature of rolling or overturning. These assumptions are not strictly true, because in the immediate vicinity of the channel bed the velocity increases with distance from the bed. Moreover, as we have seen (p. 29), the rate of increase is a diminishing rate. As a consequence of the inequality of velocity and its mode of distribution (1) the average pressure on the upstream face of a large particle is greater than the corresponding average pressure on a small particle, (2) the point of application of the total pressure (the point which determines the lever arm in overturning and rolling) is always above the center of gravity, and (3) the point of application may be differently related to the center of gravity in particles of different sizes. The general effect of these qualifying circumstances is to reduce the difficulty of moving large particles, and thus to make the rate at which competent diameter of particle increases with velocity (at any particular level) somewhat greater than that of the square of the velocity.

On the other hand, it is to be observed that in stream traction the roughness of the channel bed is defined by the coarseness of the load, and the system of velocities near the bed is a function of several things, one of which is the roughness. It is by no means impossible that the vertical velocity curve of a stream flowing over a bed of coarse débris is an enlarged replica of the curve of a shallower stream flowing over a bed of finer débris, in which case the law of Leslie might hold despite the qualifications mentioned above. The problem is too complicated, for the present at least, for full deductive treatment, and there are no adequate experimental data.

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[1] For references see footnote on page 16.

Most of the earlier experiments on competence pertained to flume traction, but it is probable that in those of T. Login (1857) the conditions were such as to give stream traction. The currents he employed were shallow, and he measured velocities by means of floats which occupied half the depth of the water.[1] As dimensions of transported particles are not included in his report of observations, a numerical formula can not be based on it.

Experimental data on competent velocity for stream traction.

[By T. Login.]

	Velocity in ft./sec.
Brick clay, mixed with water and then allowed to settle	0.25
Fresh-water sand	.67
Sea sand	1.10
Rounded pebbles, size of peas	2.00

John S. Owens, experimenting on the transporting power of sea currents, made use of small streams flowing from one tide pool to another. Measuring velocities by means of floats, he tested the ability of currents to move pebbles, 0.5 inch to 6 inches in diameter, over a channel bed of sand.[2] His results are formulated in

$$D_1 = \frac{45\ V^2}{W-64}$$

where D_1 is diameter of pebble in inches, V velocity in ft./sec., and W the weight in pounds of a cubic foot of the material of the pebble. This is equivalent to

$$D = \frac{0.059}{G-1}\ V^2 \qquad (82)$$

where D is the diameter in feet and G the density of the material.[3]

Of the Berkeley experiments on competence, recorded in Tables 9 and 10, a single series bears on the point under consideration, but its bearing is less direct than could be desired. By selecting from Table 9 data corresponding to a trough width of 1 foot and a discharge of 0.363 ft.³/sec. I was able to make a logarithmic plot of diameters of particles of grades (B), (C), (D), (E), (G) in relation to competent mean velocities, and this plot gave the following equation:

$$D = 0.0025\ V_m^{2.7} = \frac{0.0042}{G-1}\ V_m^{2.7} \qquad (83)$$

The exponent 2.7 is connected with the fact that V_m in this case is mean velocity with discharge constant. It is easy to infer from the data assembled in Table 53 that if either depth or slope had been the constant condition in the experiments a smaller exponent would be indicated. So the possibility remains that the Leslie law is true of mean velocities provided the depths increase along with the velocities, and the experimental data manifestly do not apply to bed velocities.

In order to compare the Berkeley observations with Login's, the diameters of his materials have been computed by equation (83). The diameter found for brick clay, 0.00006 foot, is much too large; but this result is readily accounted for by the fact that adhesion is an important factor in the resistance of clay to the action of the current. If the computed diameters for his "fresh-water sand," 0.00085 foot, and "sea sand," 0.0032 foot, are correct, those materials correspond severally to our grades (A) and (D), a very fine sand and a coarse sand. The diameter found for "pebbles, size of peas," is 0.016 foot, or one-fifth of an inch.

The coefficient obtained by Owens, 0.059 in equation (82), is 14 times as large as our coefficient, 0.0042 in equation (83), a contrast which accords in a general way with the difference between the classes of phenomena observed. The pebbles he tested were rolled over a bed of relatively fine material, which gave them a smooth pathway with little resistance, while the grains to be moved in our experiments rested among similar grains and were less readily dislodged.

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[1] Royal Soc. Edinburgh Proc., vol. 3, p. 475, 1857

[2] Geog. Jour., vol. 31, pp. 415–420, 1908.

[3] See also experiments by T. E. Blackwell, cited in Chapter XII.

CHAPTER VIII.—RELATION OF CAPACITY TO DEPTH.

INTRODUCTION.

As a condition controlling capacity for traction, depth has several distinct aspects; and the nature of its control depends altogether on the character of associated conditions. Three aspects will here be considered. They all assume that size of débris and width of channel are constant, and they are severally characterized by the limiting conditions of constant discharge, constant slope, and constant mean velocity. In examining the nature of the controls, and in comparing them with one another and with other controls, use will be made of the synthetic index; and the method of discussion will be similar to that of the preceding chapter. The symbols for the synthetic index, under the three limiting conditions, will be severally

I_{dQ}, I_{ds}, and I_{dV}.

WHEN DISCHARGE IS CONSTANT.

A stream of constant discharge, flowing in a channel of constant width, can change its depth only by changing its mean velocity, and depth and velocity vary in opposite senses. Whatever the ratio by which the mean velocity is increased or diminished, the depth diminishes or increases in the same ratio. It follows that the law of change for capacity in relation to mean velocity is the inverse of the law of change for capacity in relation to depth. So far as these laws are expressed by values of the synthetic indexes,

$$I_{dQ} = -I_{VQ}.$$

Independent computations of I_{dQ} are therefore unnecessary, as the values of I_{VQ} in Tables 46, 47, and 48 need only change of sign to become the corresponding values of I_{dQ}. The following summary statement of the general features of the control of capacity by depth is but a condensation and adaptation of the statement on pages 157–158.

Under the condition of constant discharge capacity varies inversely with depth. Its rate of variation is more than twice the rate at which it varies with slope of channel. The rate responds to changes in discharge, slope of channel, fineness of débris, and form ratio, diminishing as those factors increase (with possible exception as to form ratio).

Depth, when subject to the condition of constant discharge, varies inversely with slope. Estimates of the average rate of variation are contained in the last column of Table 48.

WHEN SLOPE IS CONSTANT.

A stream flowing down a constant slope, in a channel of constant width, and transporting débris of a particular grade changes its depth when the discharge is changed. The depth is greater as the discharge is greater. The capacity for traction also is greater as the discharge is greater. Therefore the capacity varies in the same sense as the depth.

Table 54 contains 68 values of I_{ds}, computed from data of Tables 12 and 14. The method of derivation was identical with that already described for Table 49, with the exception that values of depth were used instead of values of mean velocity.

TABLE 54.—*Values of I_{ds}, the synthetic index of relative variation for capacity in relation to depth of current, when slope is constant.*

Grade.	S	Value of I_{ds} for width (feet) of—					
		0.23	0.44	0.66	1.00	1.32	1.96
(A)	0.6	....	....	....	....	2.31	2.28
(B)	.6	....	....	2.02	2.40	2.93	2.14
	1.0	1.07	2.17	2.05	2.18	2.52	1.85
	1.4	.89	....	1.78	1.97	2.36	1.41
	2.0	....	....	1.59	1.83	....	....
(C)	.6	....	3.44	2.27	2.51	2.56	3.29
	1.0	....	2.12	1.98	2.22	2.85	2.13
	1.4	....	1.80	2.34	2.04	2.36	2.65
	2.0	....	....	2.27	2.22	....	....
(D)	.6	....	....	1.84	1.97	2.03	....
	1.0	....	....	2.18	2.30	2.12	....
	1.4	....	....	2.01	2.16	....	....
	2.0	....	....	1.87	2.75	....	....
(E)	.6	....	....	....	1.90	....	....
	1.0	....	....	1.02	1.70	....	....
	1.4	....	....	1.09	1.79	....	....
	2.0	....	....	....	2.00	....	....
(F)	1.4	....	....	2.40	3.59	....	....
	2.0	....	....	2.03	2.87	....	....
(G)	1.0	....	....	2.74	3.02	3.88	....
	1.4	....	....	2.18	2.91	3.07	....
	2.0	....	....	1.96	2.51	3.01	....
(H)	1.0	....	....	2.37	....	....	....
	1.4	....	....	2.95	....	....	....
	2.0	....	....	2.22	....	....	....

The derivation of means in Table 55 followed the precedents of Tables 47 and 50. An examination of logarithmic plots shows that I_{ds} varies inversely, but only slightly, with discharge. The means in Table 55 show that it varies inversely with slope and fineness, but they give no clear indication of its essential relation to width.

TABLE 55.—*Partial means based on Table 54, illustrating the control of I_{ds}, by slope, fineness, and width.*

Number of values.	Means of I_{ds} for slope (per cent) of –							
	0.6	1.0	1.4	2.0				
14	2.66	2.13						
18		2.12	2.10					
13			2.40	2.24				
	Means of I_{ds} for grade—							
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
2	2.29	2.53						
15		2.08	2.39					
10		2.13	2.33	2.12				
6			2.22	2.23	1.55			
4			2.22	2.20		2.72		
8			2.28				2.78	
3		1.81	2.20	2.02			2.29	2.51
	Means of I_{ds} for width (feet) of—							
	0.23	0.44	0.66	1.00	1.32	1.96		
2	0.98		1.91					
4		2.38	2.16					
19			1.98	2.36				
11				2.37	2.70			
6					2.59	2.24		

For each of the 68 values of I_{ds}, the corresponding value of the synthetic index of the relation of capacity to discharge, I_3, was computed, the relations being such that the paired values represent exactly the same conditions. It was found that, without exception, the values of I_{ds} are greater than the companion values of I_3. Table 56 contains a series of comparative means and their ratios, the ratio of general means being 1.62.

TABLE 56.—*Synthetic indexes, comparing the control of capacity by depth with the control by discharge, and comparing both controls with grades of débris.*

Grade.	Number of separate determinations.	Mean I_{ds}.	Mean I_3.	$\frac{\text{Mean } I_{ds}}{\text{Mean } I_3}$	$\frac{\text{Mean } I_3}{\text{Mean } I_{ds}}$
(A)	2	2.29	1.37	1.67	0.60
(B)	17	1.95	1.30	1.50	.67
(C)	17	2.41	1.36	1.77	.56
(D)	10	2.12	1.26	1.68	.59
(E)	6	1.58	0.99	1.59	.63
(F)	4	2.72	1.81	1.50	.67
(G)	[illegible]	2.81	1.76	1.59	.63
(H)	3	2.51	1.70	1.48	.68
	68	2.25	1.39	1.62	.62

DEPTH VERSUS DISCHARGE.

The comparison of I_{ds} with I_3 affords, incidentally, an estimate of the relative variation of depth and discharge. The rate of variation of capacity with depth being I_{ds}, the rate of variation of depth with capacity is $1/I_{ds}$; and, the rate of variation of capacity with discharge being I_3, the rate of variation of depth with discharge is $1/I_{ds} + I_3 = I_3/I_{ds}$. The values of I_3/I_{ds} in Table 56 are therefore estimates of the variation of depth in relation to discharge, under the limiting condition of constant slope. They are of the quality of the synthetic index and are based on the general range of conditions realized in the laboratory, except those in the neighborhood of competence. For this range of conditions depth varies, on the average, with the 0.62 power of discharge.

WHEN VELOCITY IS CONSTANT.

By interpolation from the data recorded in Tables 12 and 14, values of capacity and depth may be found corresponding to selected values of mean velocity. Such values were derived for mean velocities of 2, 3, and 4 ft./sec., and from them were computed the 42 values of I_{dV} in Table 57.

TABLE 57.—*Values of I_{dV}, the synthetic index of relative variation for capacity in relation to depth of current, when mean velocity is constant.*

Grade.	V_m	Value of I_{dV} for width (feet) of—					
		0.23	0.44	0.66	1.00	1.32	1.96
(A)	3					−0.32	−0.75
	4						− .69
(B)	2			+0.09	−0.26	+ .25	+ .32
	3	−0.26	−0.48	− .14	−1.02	+ .18	+ .19
	4			− .34		− .37	
(C)	2		− .75	0	+ .21	+ .22	
	3			− .57	− .36	− .32	
	4			+ .09	− .25	− .35	
(D)	[illegible]			− .34	− .27	+ .08	−1.50
	3			− .22	− .75	− .92	− .44
	4				−1.50		
(E)	2				−1.03		
	3				− .93		
(G)	3			−1.08	−1.35		
	4			−2.69	−1.19	−3.17	
(H)	3			− .75			

Most of these values are negative, but nine are positive. The mean of the 42 values, combined with regard to sign, is −0.54. A positive value, considered by itself, indicates that capacity varies directly with depth, and a negative value that the variation is inverse. At least two interpretations may be considered—(1) that the actual variation is usually inverse but under some conditions is direct; (2) that the law of inverse variation is general and that the apparent exceptions are due entirely to the imperfection of the data. The second interpretation accords the better with the analogies afforded by other branches of the subject and is provisionally accepted.

The interpretation directs attention to the general discordance of the computed values of I_{dv}, and a suggestion may be made as to the cause of that discordance. First, the measurement of depth was the most difficult of the direct measurements performed in the laboratory, and it was peculiarly subject to possibilities of systematic error. Second, the range of slopes through which depth could be observed was much less than in the case of capacity, and this made the work of adjustment less satisfactory. Third, in the computation of this particular index the depth data enter twice, and they enter in such way that their errors cumulate instead of canceling.

In Table 58 the relations of I_{dv} to various conditions are shown by the comparison of corresponding means. I_{dv} is seen to vary directly with mean velocity, and it may fairly be inferred to vary inversely with fineness, but the data as to width of channel are contradictory and inconclusive.

The control of the index by mean velocity affords information as to its relation to slope and discharge. Mean velocity varies directly with both slope and discharge, and it does not change without corresponding change in at least one of these factors. It follows that the index, which varies directly with mean velocity, also varies directly with at least one of the factors slope and discharge. In the groups of data from which values of the index were computed, increase of velocity was associated either with increase of slope or with increase of both slope and discharge but in no case with decrease of slope or discharge. It seems, therefore, proper to infer that I_{dv} varies in magnitude directly with both slope and discharge. In this respect it stands as an exception among the indexes of relative variation connected with traction. All other species of I and also i vary inversely with slope and discharge. As a check on this exceptional result, certain probable errors have been computed. In the upper division of Table 58 −0.19, the mean of 12 values of I_{dv} with a velocity of 2 ft./sec., is compared with −0.41, the corresponding mean for a velocity of 3 ft./sec. The difference between these means, −0.22, has a probable error of ±0.13. A similar difference, appearing in the comparison of indexes for velocities of 3 and 4 ft./sec., is −0.24±0.18. As the two differences give testimony of the same tenor, their joint evidence is stronger than that of either separately, so that the discussion of the residuals leaves the presumption in favor of the conclusion that this particular index constitutes a real exception in its relation to slope and discharge.

TABLE 58.—*Partial means based on Table 57, illustrating the control of I_{dv}, by mean velocity, fineness and width.*

Number of values.	Mean of I_{dv} for mean velocity (ft./sec.) of—		
	2	3	4
12	−0.19	−0.41	
9		− .57	−0.81

Number of values.	Mean of I_{dv} for grade—							
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
2	−0.54	+0.18						
10		− .11	−0.32					
7			− .15	−0.57				
2				− .51	−0.98			
5			− .29				−1.90	
1							−1.08	−0.75

Number of values.	Mean of I_{dv} for width (feet) of—					
	0.23	0.44	0.66	1.00	1.32	1.96
1	−0.26	−0.48				
2		− .61	−0.07			
9			− .64	−0.58		
8				− .49	−0.61	
5						−0.44

THE THREE CONDITIONS COMPARED.

When depth is increased without change of slope (or width or grade of débris), its increase is effected by increase of discharge, with the result that capacity is increased, so that capacity is an increasing function of depth. When depth is increased without change of discharge, its increase is effected by reducing slope, with the result that capacity is reduced, so that capacity is a decreasing function of depth. When depth is increased without change of velocity, its increase requires increase of discharge accompanied by diminution of slope; and as these changes have opposite influences on capacity, it is not evident a priori whether capacity will be enlarged or reduced. The experimental data show that it is slightly reduced, so that capacity is a decreasing function of depth.

When depth is reduced without change of slope, and the reduction is continued progressively, a stage is eventually reached in which the velocity is no longer competent for traction. It is probable, therefore, that, under this condition, an approximate formula for $C=f(d)$ might involve a depth constant and be similar to the formula (64) used for $C=f(Q)$.

Reduction of depth without change of discharge involves increase of velocity, and it is evident that competence does not lie in that direction. But increase of depth involves reduction of velocity and leads eventually to a competent velocity. The limiting depth corresponding to competence is therefore a great depth instead of a small one. As mean velocity now varies inversely with depth, a coordinate formula might take the form

$$C=B\left(\frac{1}{d}-\frac{1}{\delta}\right)^n$$

B being used as a general constant and δ as a constant depth.

When depth is reduced without change of mean velocity, the efficiency of the mean velocity is enhanced and competence is not approached. When depth is increased, the efficiency of the unchanged mean velocity is diminished and a (large) competent depth may, under some conditions, be realized.

To show the numerical relations of the indexes by which these three capacity-depth functions are severally characterized, certain means are assembled in Table 59. It was not found possible to procure values of the different indexes representing closely the same conditions, and what was done was to derive for each index the mean of all determinations made for each particular grade of débris.

The arrangement by grades points again to the fact that all the indexes vary inversely with fineness of débris, but the rate of variation is in fact somewhat greater than these series of values suggest. The observations on the coarser grades were made with steeper average slopes and larger average discharges than those on the finer grades, and the effect of high slopes and large discharges (except in case of I_{dv}) is to reduce the indexes of relative variation.

TABLE 59.—*Comparison of synthetic indexes of relative variation for capacity and depth, under the several conditions of constant discharge, constant slope, and constant mean velocity.*

Grade.	Number of separate determinations.			Means.			$\frac{I_{dQ}}{I_{ds}}$
	I_{dQ}	I_{ds}	I_{dv}	I_{dQ}	I_{ds}	I_{dv}	
(A)	5	2	3	− 3.62	2.29	−0.59	−1.57
(B)	18	17	12	− 4.24	1.95	− .15	−2.17
(C)	19	17	12	− 3.58	2.41	− .33	−1.49
(D)	9	10	7	− 4.39	2.12	− .56	−2.07
(E)	5	6	2	− 5.17	1.58	− .98	−3.29
(F)	5	4	.....	− 8.73	2.72	....	−3.21
(G)	9	9	5	− 9.45	2,81	−1.30	−3.36
(H)	3	3	1	−10.01	2.51	− .75	−3.99
	73	68	42	− 5.28	2.25	− .56	−2.34

From the general means at the bottom of the table it appears that, for the range of laboratory conditions, capacity is 2.34 times as sensitive to the control of depth when the limiting condition is constant discharge as when the limiting condition is constant slope, and about nine times as sensitive as when the limiting condition is constant mean velocity.

One of the results of the discussion is to emphasize the importance, when considering the relation of tractional work to depth, of sharply discriminating the conditions under which depth is regarded as a variable.

So far as the variations of the capacity-depth indexes admit of formulation in the symbols used for other indexes,

$$I_{dQ}=f\ (\grave{S}\ \grave{Q}\ \grave{F}) \qquad (84)$$

$$I_{ds}=f_{I}\ (\grave{S}\ \grave{Q}\ \grave{F}) \qquad (84a)$$

$$I_{dv}=f_{II}\ (\acute{S}\ \acute{Q}\ \grave{F}) \qquad (84b)$$

COMPARISON OF CONTROLS BY SLOPE, DISCHARGE, MEAN VELOCITY, AND DEPTH.

In Chapter V the general sensitiveness of capacity to slope is compared with that of capacity to discharge by means of coordinate values of the exponent i. In Chapter VII the sensitiveness to slope is compared with sensitiveness to mean velocity (with discharge constant) by means of coordinate values of I. The two methods of comparison are so far related that their results should be fairly harmonious. In the present chapter the same measure of sensitiveness to mean velocity, converted by change of sign to a measure of sensitiveness to depth (with discharge constant), has been compared with a similar measure for depth with slope constant. Finally, the measure last mentioned has been compared with a coordinate measure of the sensitiveness of capacity to discharge, thus completing a circle and affording opportunity for a checking of estimates in respect to consistency. The ratios resulting from the four comparisons are as follows:

$$\frac{\text{index of control by slope}}{\text{index of control by discharge}}=1.36$$

$$\frac{\text{index of control by velocity (discharge constant)}}{\text{index of control by slope}}=2.60$$

$$\frac{\text{index of control by depth (slope constant)}}{\text{index of control by discharge}}=-1.62$$

$$\frac{\text{index of control by velocity (discharge constant)}}{\text{index of control by depth (slope constant)}}=-2.34$$

The combination, by multiplication, of the first and second equations gives

$$\frac{\text{index of control by velocity (discharge constant)}}{\text{index of control by discharge}}=3.51$$

The combination of the third and fourth gives an equation with identical first member, but the second member is 3.79. The two results differ by 8 per cent.

ADJUSTMENT AND NOTATION.

The tractional load of a natural stream includes particles with great range in size. The grades of débris used in the laboratory had narrowly limited ranges. Although the reasons for this limitation were believed to be adequate, the possibility was recognized that the laws discovered by the use of artificial grades might not apply without modification to natural grades; and in view of this possibility a series of experiments were arranged to bridge over the interval between the artificial and the natural in this particular respect. The same apparatus and the same general methods being used, observations were made first on mixtures of two grades, then on mixtures of three or more, and finally on a natural combination of sizes.

When work on mixtures was begun, need was soon found for a modification of the experimental procedure. During the automatic process of adjusting the slope to the load the current acted unequally on the components of the mixture, carrying forward an undue share of the finer part and depositing an undue share of the coarser. To escape the difficulties introduced by this partial re-sorting, a run was interrupted after it had gone far enough to indicate the approximate slope, the débris was taken from arrester and experiment trough and was throughly remixed, and then the approximate slope was artificially constructed in the trough, after which the run was continued.

The observational data are contained in divisions (J) and (K) of Table 4. The values of capacity in relation to slope were adjusted in the same manner as with individual grades, except that each value of σ for an adjusting equation was derived from the data of the particular observational series, without influence from related series. The adjusted capacities are recorded in Table 60, and with them are fractional capacities computed for the several grades composing the mixtures. Table 17 contains the constants of the adjusting equations and also series of values of the index of relative variation.

In each set of experiments with mixture of two grades the proportions of the components were varied. The usual series of proportions was approximately 4 : 1, 2 : 1, 1 : 1, 1 : 2, and 1 : 4. To denote these mixtures, a notation has been adopted similar to one employed in chemistry; for example, a mixture of grades (B) and (F) in the proportion 4 : 1 is designated (B_4F_1).

The proportions of some of the mixtures are told accurately by the subscript figures; those of others only approximately. The theoretic or standard mode of apportionment was by weight of dry material, but when this was not convenient the material was weighed or measured in moist or saturated condition, and the actual ratio for dry weight was afterward learned by computation. The actual proportions are given in percentages in Table 4 (J).

TABLE 60.—*Adjusted values of capacity in relation to slope, for mixtures of two or more grades of débris and for an unsorted natural alluvium, based on data of Table 4 (J) and (K).*

Grade	(A_1C_1)			(A_3G_1)			(A_2G_1)			(A_1G_1)		
Q	0.363			0.363			0.363			0.363		
Component	(A)	(C)	Total.	(A)	(G)	Total.	(A)	(G)	Total.	(A)	(G)	Total.
S	Value of C.											
0.5	16	16	32	13	4	17	13	7	20	8	9	17
.6	23	23	46	22	7	29	21	10	31	11	12	23
.7	30	30	60	32	11	43	29	15	44	14	15	29
.8	37	37	74	44	15	59	39	19	58	18	19	37
.9	44	44	88	57	19	76	49	24	73	22	23	45
1.0	51	51	102	71	23	94	60	30	90			
1.2	65	66	131	99	33	132	85	42	127	32	33	65
1.4	80	81	161	131	44	175	113	56	169	44	45	89
1.6	95	96	191	165	55	220				57	58	115
1.8												
2.0												
Probable error (per cent)						2.8			4.6			

TABLE 60. —*Adjusted values of capacity, in relation to slope, for mixtures of two or more grades of débris and for an unsorted natural alluvium, based on data of Table 4 (J) and (K)*—Continued.

Grade	(A_1G_2)			(A_1G_4)			(B_4F_1)			(B_2F_1)		
Q	0.363			0.363			0.363			0.363		
Component	(A)	(G)	Total.	(A)	(G)	Total.	(B)	(F)	Total.	(B)	(F)	Total.
S	Value of *C*.											
0.5							26	7	33	22	12	34
.6							37	10	47	29	17	46
.7							48	14	62	38	21	59
.8							60	17	77	47	25	72
.9							72	20	92	54	30	84
1.0	7	14	21	3	9	12	83	23	106	62	35	97
1.2	10	21	31	4	14	18	107	30	137	78	43	121
1.4	14	28	42	5	20	25	133	37	170	93	52	145
1.6	19	37	56	7	26	33				109	61	170
1.8				9	34	43						
2.0				12	42	54						
Probable error (per cent)									2.1			1.1

Grade	(B_1F_1)			(B_1F_2)			(B_1F_4)			(C_4E_1)		
Q	0.363			0.363			0.363			0.363		
Component	(B)	(F)	Total.	(B)	(F)	Total.	(B)	(F)	Total.	(C)	(E)	Total.
S	Value of *C*.											
0.5												
.6										29	8	37
.7	22	24	46				2	11	13	40	11	51
.8	26	30	56	9	19	28	3	13	16	51	14	65
.9	31	35	66	11	23	34	4	15	19	62	17	79
1.0	37	41	78	12	28	40	5	18	23	74	20	94
1.2	48	55	103	17	37	54	6	25	31	97	26	123
1.4	61	68	129	21	48	69	7	32	39	122	32	154
1.6	75	83	158	26	59	85	9	40	49	146	39	185
1.8	89	100	189							171	46	217
Probable error (per cent)			0.1									0.7

Grade	(C_2E_1)			(C_2E_1)			(C_1E_1)			(C_1E_1)		
Q	0.182			0.363			0.182			0.363		
Component	(C)	(E)	Total.	(C)	(E)	Total.	(C)	(E)	Total.	(C)	(E)	Total.
S	Value of *C*.											
0.5												
.6				20	11	31						
.7				28	15	43				14	15	29
.8				36	19	55				19	21	40
.9				44	24	68	12	12	24	25	26	51
1.0				53	28	81	14	15	29	30	32	62
1.2				70	37	107	19	20	39	42	44	86
1.4				88	47	135	24	26	50	53	57	110
1.6	44	24	68	106	57	163	29	32	61	65	71	136
1.8	55	29	84	124	67	191	36	38	74	78	84	162
2.0	66	35	101				42	46	88	90	97	187
2.2	77	42	119				53	58	111			
Probable error (per cent)						0.7			1.8			2.3

TABLE 60. –*Adjusted values of capacity, in relation to slope, for mixtures of two or more grades of débris and for an unsorted natural alluvium, based on data of Table 4 (J) and (K)*—Continued.

Grade	(C_1E_2)			(C_1E_2)			(C_1E_4)			(C_1E_4)		
Q	0.182			0.363			0.182			0.363		
Component	(C)	(E)	Total.	(C)	(E)	Total.	(C)	(E)	Total.	(C)	(E)	Total.
S	Values of *C*.											
0.5	......	......	......	......	......	......	......	......	......	......	......	......
.6	......	......	......	......	......	......	......	......	......	......	......	......
.7	......	......	......	8	17	25	......	......	......	......	......	......
.8	......	......	......	11	23	34	......	......	......	......	......	......
.9	......	......	......	13	29	42	3	13	16	6	28	34
1.0	7	15	22	16	35	51	4	15	19	8	33	41
1.2	9	21	30	22	48	70	5	20	25	11	46	57
1.4	12	27	39	28	63	91	6	26	32	14	61	75
1.6	15	34	49	34	77	111	8	32	40	18	76	94
1.8	18	41	59	42	92	134	9	39	48	21	92	113
2.0	22	48	70	48	108	156	11	45	56	25	109	134
2.2	25	55	80	56	124	180	12	53	65	......	......	......
Probable error (per cent)	......	......	2.2	......	......	5.6	......	......	0.1	......	......	1.6

Grade	(C_4G_1)			(C_2G_1)			(C_1G_1)			(C_1G_2)		
Q	0.363			0.363			0.363			0.363		
Component	(C)	(G)	Total.	(C)	(G)	Total.	(C)	(G)	Total.	(C)	(G)	Total.
S	Values of *C*.											
0.5	17	4	21	11	6	17	......	......	......	......	......	......
.6	24	6	30	19	9	28	......	......	......	......	......	......
.7	32	8	40	27	14	41	10	10	20	......	......	......
.8	42	10	52	36	18	54	15	16	31	......	......	......
.9	54	13	67	45	23	68	21	22	43	4	8	12
1.0	65	16	81	55	27	82	27	28	55	6	12	18
1.2	93	23	116	74	37	111	40	40	80	11	22	33
1.4	126	32	158	96	48	144	53	53	106	17	33	50
1.6	164	41	205	119	59	178	67	67	134	23	47	70
1.8	208	52	260	141	71	212	80	81	161	31	61	92
2.0	......	......	......	......	......	......	......	......	......	......	......	......
Probable error (per cent)	......	......	1.9	......	......	1.2	......	......	4.4	......	......	2.2

Grade	(E_4G_1)			(E_2G_1)			(E_1G_1)			(E_1G_2)		
Q	0.363			0.363			0.363			0.363		
Component	(E)	(G)	Total.	(E)	(G)	Total.	(E)	(G)	Total.	(E)	(G)	Total.
S	Value of *C*.											
0.6	10	2	12	......	......	......	......	......	......	......	......	......
.7	13	3	16	6	3	9	......	......	......	......	......	......
.8	17	4	21	9	5	14	8	8	16	......	......	......
.9	21	5	26	13	7	20	10	10	20	4	9	13
1.0	25	6	31	18	9	27	13	13	26	6	11	17
1.2	35	9	44	29	15	44	18	19	37	8	16	24
1.4	47	12	59	43	22	65	24	25	49	11	22	33
1.6	60	15	75	59	30	89	31	31	62	14	29	43
1.8	75	19	94	......	......	......	37	38	75	18	37	55
2.0	......	......	......	......	......	......	......	......	......	23	45	68
Probable error (per cent)	......	......	......	......	......	......	......	......	......	......	......	1.4

TABLE 60. -*Adjusted values of capacity, in relation to slope, for mixtures of two or more grades of débris and for an unsorted natural alluvium, based on data of Table 4 (J) and (K)*—Continued.

Grade	$(A_1C_1G_2)$				$(C_{45}D_{35}E_{12}F_6G_2)$											
Q	0.363				0.182						0.363					
Component	(A)	(C)	(G)	Total.	(C)	(D)	(E)	(F)	(G)	Total.	(C)	(D)	(E)	(F)	(G)	Total.
S	Value of *C*.															
0.6	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
.7	2	2	5	9	8.2	6.6	2.3	1.1	0.3	18.9	24.2	18.9	6.5	3.2	1.1	54
.8	4	4	9	17	10.6	8.2	2.8	1.4	.5	23.5	29.2	22.8	7.8	3.9	1.3	65
.9	7	7	13	27	12.8	10.0	3.4	1.7	.6	28.4	35.0	27.3	9.4	4.7	1.6	78
1.0	9	9	20	38	15.2	11.8	4.1	2.0	.7	33.9	40.9	31.8	10.9	5.4	1.8	91
1.2	16	16	33	65	20.3	16.0	5.5	2.7	.9	45.8	53.5	41.6	14.3	7.1	2.4	119
1.4	24	24	50	98	26.6	20.6	7.1	3.5	1.2	59	67.5	52.5	18.0	9.0	3.0	150
1.6	34	34	69	137	32.8	25.6	8.8	4.4	1.5	73	81.9	63.7	21.8	10.9	3.6	182
1.8	45	45	91	181	39.6	30.8	10.6	5.3	1.8	88	95.4	74.2	25.4	12.7	4.2	212
2.0	...	...	...	...	47.3	36.8	12.6	6.3	2.1	105	...	...	...	...	...	...
Probable error (per cent)	...	...	...	4.0	...	...	...	...	...	...	...	...	...	...	...	0.4

Grade	$(C_{45}D_{35}E_{12}F_6G_2)$.						Natural.	
Q	0.545						0.182	0.363
Component	(C)	(D)	(E)	(F)	(G)	Total.		
S	Values of *C*.							
0.4	...	...	...	...	...	...	...	17
.5	...	...	...	...	...	...	...	26
.6	36.4	28.4	9.7	4.8	1.6	81	...	36
.7	44.1	34.3	11.8	5.9	2.0	98	15	47
.8	50.4	39.9	13.7	6.8	2.3	114	20	60
.9	59.4	46.2	15.8	7.9	2.6	132	26	75
1.0	68.0	52.8	18.1	9.0	3.0	151	33	91
1.2	85.0	66.1	22.7	11.3	3.8	189	47	126
1.4	103	80.2	27.5	13.7	4.6	229	63	168
1.6	121.5	94.5	32.4	16.2	5.4	270	80	213
1.8	...	...	...	...	...	...	98	...
2.0	...	...	...	...	...	...	117	...
2.2	...	...	...	...	...	...	138	...
2.4	...	...	...	...	...	...	159	...
2.6	...	...	...	...	...	...	181	...
Probable error (per cent)	...	...	...	...	...	0.4	2.6	0.8

MIXTURES OF TWO GRADES.

The relation borne by the traction of mixtures to the traction of separate grades is most clearly shown by the records from varied combinations of two grades only. In all experiments with mixtures the same width of channel, 1 foot, was used; and from the adjusted capacities for mixtures of two it is possible to select a full set associated with the same discharge, 0.363 ft.³/sec., and the same slope, 1.4 per cent. These capacities are arranged for comparative examination in Table 61, and to them are added, from Table 12, the corresponding capacities for the separate grades.

TABLE 61.—*Capacities for traction, with varied mixtures of two grades.*

Grade.	Capacities.			Grade.	Capacities.			Grade.	Capacities.			Grade.	Capacities.			Grade.	Capacities.		
	Total.	(A)	(G)		Total.	(C)	(G)		Total.	(B)	(F)		Total.	(C)	(E)		Total.	(E)	(G)
(A)	185	185	0	(C)	143	143	0	(B)	149	149	0	(C)	143	143	0	(E)	62	62	0
(A_3G_1)	175	131	44	(C_4G_1)	158	126	32	(B_4F_1)	170	133	37	(C_4E_1)	154	122	32	(E_4G_1)	59	47	12
(A_2G_1)	169	113	56	(C_2G_1)	144	96	48	(B_2F_1)	145	93	52	(C_2E_1)	135	88	47	(E_2G_1)	65	43	22
(A_1G_1)	89	44	45	(C_1G_1)	106	53	53	(B_1F_1)	129	61	68	(C_1E_1)	110	53	57	(E_1G_1)	49	24	25
(A_1G_2)	42	14	28	(C_1G_2)	50	17	33	(B_1F_2)	69	21	48	(C_1E_2)	91	28	63	(E_1G_2)	33	11	22
(A_1G_4)	25	5	20	(G)	16	0	16	(B_1F_4)	39	7	32	(C_1E_4)	75	14	61	(G)	16	0	16
(G)	16	0	16	...	...	...	...	(F)	33	0	33	(E)	62	0	62	...	...	...	...

Each vertical column of capacities shows the tractional power of the current, first for the finer component alone, then for mixtures with progressively increasing shares of the coarser component, and finally for the coarser alone. The order of the different groups is that of the contrast in fineness between the finer and coarser components. If the linear fineness of the finer be divided, in each case, by the fineness of the coarser, the ratios obtained are

(AG)	(CG)	(BF)	(CE)	(EG)
16.2	9.7	8.5	3.4	2.9

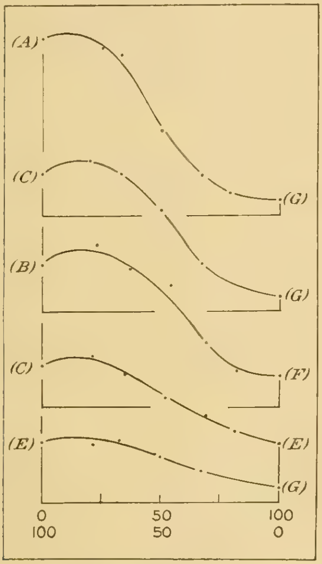

FIGURE 55.—Tractional capacity for mixed débris, in relation to proportions of component grades.

The data of the table are plotted, with a different arrangement, in figures 55 and 56. In figure 55 the total capacities are plotted in relation to the proportions of fine and coarse in the mixtures. The vertical scale being of capacity, the horizontal, if read from right to left, is of percentage of the finer component, or if read from left to right, is of percentage of the coarser. Figure 56 (p. 174) shows, in parallel columns, the capacities for the component grades, those for the coarser components being at the left.

Attention may first be directed to the total capacity curves of figure 55. If the capacities for mixtures were related in the simplest manner to the proportions of components, the curve of capacities would be a straight line joining the points (at the extreme left and extreme right) given by the capacities for the components. The (EG) curve—that placed lowest in the diagram—lying wholly above such a hypothetic line, would suggest that all mixtures give an advantage in traction, but this suggestion is not supported by the other curves. The upper curve, for example, would lie as much below as above a straight line joining its extremities. The capacity for the mixture appears always to exceed what may be called the pro rata estimate when the finer component has the higher proportion, but it may fall below that estimate when the coarser component predominates.

The curves of figure 56 show the capacities apportioned to the components of the mixtures. Each one represents that portion of the total load which consists of the material of one component. In each curve of the left-hand column the ordinate at the right represents the load of the coarser material when by itself, and the successive ordinates toward the left show how the load is modified by the admixture, in the material fed to the current, of gradually increasing percentages of the finer débris. There are no observations with very small percentages of the finer material, but in each case the second fixed point of the curve shows an increase of load. The addition of the finer débris not only increases the total capacity but increases the capacity for the coarser débris. The amount of the latter increase appears to be greater as the contrast in fineness of components is greater, and in the extreme case the capacity for the coarser is multiplied by 3.5. The capacity of the current for débris of grade (G) is 16 gm./sec.; but when that débris is mixed with twice its weight of grade (A), which is 16.2 times as fine, the capacity for the mixture is so large that one-third of it, apportioned to grade (G), is 56 gm./sec. In three of the five suites of experiments the highest capacity recorded for the coarser débris corresponds to the mixture of 1:1. In the others it corresponds approximately to 2:1 and 1:2. If the position of the maximum is related to contrast in fineness, it is associated with a larger ratio of the finer component when the contrast is great.

The corresponding curves for the finer component (at the right in fig. 56) show that capacity for finer débris is influenced by the admixture of coarser, but not in the same way. Each addition of the coarser reduces capacity, the rate of reduction being at first gradual, then more rapid, and afterward gradual.

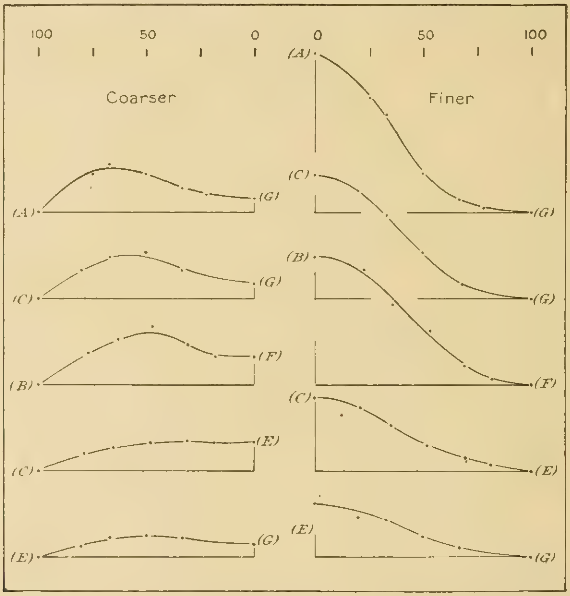

FIGURE 56.—Tractional capacities of components of mixed grades, in relation to the percentages of the components in the mixtures. Curves at left show capacities for coarser component, at right for finer. Ratios at left show percentages of finer component, at right of coarser.

The general effect of the addition of fine material being to increase capacity, and the effect of adding coarse material to reduce capacity, let us now inquire the effect of diversifying the material of the load by exchanging part of it for a finer grade and part for a coarser. Probably no general answer to this question may be derived from our data, but a partial answer is possible if we assume that the initial grade is separated from each of the substituted components by the same contrast of fineness, expressed as a ratio. To take a concrete example, from Table 61, the capacity for grade (A) is 185 gm./sec., for grade (G) 16 gm./sec., and for (A_1G_1), their equal mixture, 89 gm./sec. When for half of (A) there is substituted an equal amount of (G), which is 16.2 times coarser, the capacity is changed in the ratio $\frac{89}{185}=0.48$. When for half of (G) there is substituted an equal amount of (A), which is 16.2 times finer, the capacity is changed in the ratio $\frac{89}{16}=5.56$. The geometric mean of these ratios, 1.64, may plausibly stand for the effect of substituting an equal mixture of (A) and (G) for a grade symmetrically intermediate between (A) and (G). The method is easily criticized, and its assumptions will certainly not bear close scrutiny, but it nevertheless yields a sort of composite which is of use in showing that the general effect of diversifying a stream's tractional load is to enlarge capacity. Corresponding composite ratios have been obtained from the other examples of Table 61 and are given below.

Grade.	Ratio of fineness.	Ratio of capacity change attributed to mixture.
(AG)	16. 2	1. 64
(CG)	9. 7	2. 22
(BF)	8. 5	1. 72
(CE)	3. 4	1. 17
(EG)	2. 9	1. 56

The composite ratios have been arranged in the order of the ratio of fineness, but the comparison shows no correspondence. They prove equally inharmonious when compared with the fineness of the finer component, the fineness of the coarser component, or the fineness of the mixture. Their irregularities must be ascribed to observational errors and to causes not at present to be discriminated from observational errors. It is of interest, however, to note that the large measure of capacity change associated with the (CG) combination might be inferred also from a comparison which involves a different viewpoint and also some practically independent data. If we think of grades (A), (C), and (E) as modifiers of capacity for grade (G), we may compare their efficiencies by means of the following quantities, taken from Table 61:

Grade.	Capacity.	Grade.	Capacity.
(A_1G_1)	89	(A_1G_2)	42
(C_1G_1)	106	(C_1G_2)	50
(E_1G_1)	49	(E_1G_2)	33

The superiority of grade (C) as a modifier for (G) is thus brought out without making use of the capacities for the uncombined grades (A), (C), (E), and (G); and the result from mixtures of 1:1 is supported by that from mixtures of 1:2.

CONTROL BY SLOPE AND DISCHARGE.

The preceding comparisons are conditioned by a discharge of 0.363 ft.^{3}/sec., a slope of 1.4 per cent, and a channel width of 1 foot. With a different set of conditions a different set of quantitative relations would be found, and the qualitative also would doubtless be modified. The observations on mixtures included no other width, and there was but a single set of experiments using a different discharge, but the range in slope was coordinate with that for the separate grades.

Figure 57 shows the capacity-slope curves for the (AG) set of experiments, figure 58 for the (BF) set, and figure 59 for the (CE) set. In figure 57 the curves for mixtures form a graded series between those for the component grades, and there is almost perfect harmony of form and attitude. As the points representing capacities associated with a slope of 1.4 per cent all lie in the same vertical line, and as similar points for another slope lie in some other vertical line, it is evident by inspection that inferences from data of any other available slope would be practically identical with those from the slope of 1.4 per cent. It is also evident that indexes of relative variation, i_1 or I_1, for the mixtures constitute, with those for the components, an orderly system. The same remarks apply also to the (CE) groups of curves, but they do not apply to the (BF) group in figure 58. The attitudes of the curves for mixtures are there out of harmony with the attitudes of the (B) and (F) curves. The curves for the mixtures seem to belong to a

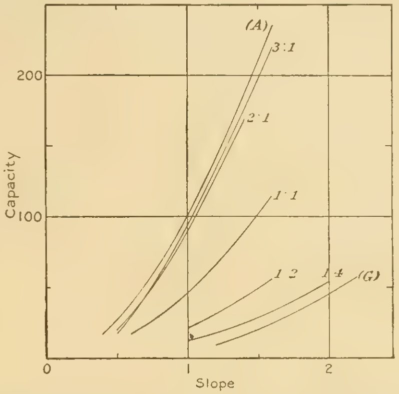

FIGURE 57. Curves of capacity in relation to slope for grade (A), grade (G), and mixtures of those grades. The ratios of components in the mixtures are indicated.

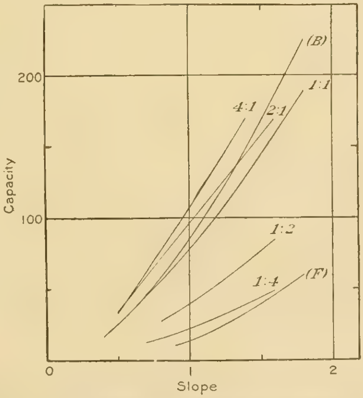

FIGURE 58. Curves of capacity in relation to slope for grade (B), grade (F), and mixtures of those grades. The ratios of the components in the mixtures are indicated.

different system, intersecting or tending to intersect the curves for the components. Evidently the indexes of relative variation are inharmonious, and evidently the inferences drawn from data for the slope of 1.4 per cent would not be duplicated by a discussion of data from a slope of 1.0 per cent or 1.6 per cent.

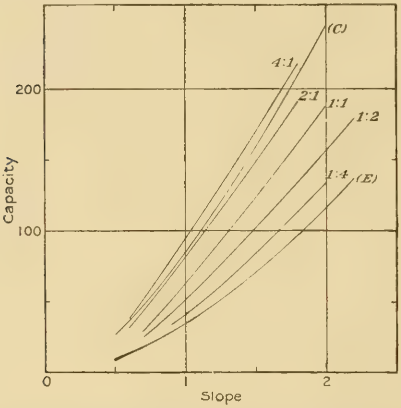

FIGURE 59.—Curves of capacity in relation to slope for grade (C), grade (E), and mixtures of those grades. The ratios of the components in the mixtures are indicated.

Graphic comparison has been extended to the remaining data of Table 60, so far as dual mixtures are concerned, but no marked discordance has been discovered outside of the (BF) group. Although the cause of the exceptional discordance has not been found, I believe that it should be ascribed to some exceptional though unknown circumstance and not be permitted to nullify the otherwise harmonious testimony. The tenor of that testimony is that the relation of capacity to slope is substantially the same for mixtures as for simpler grades of débris. There is, however, a noteworthy qualification to this statement, in that the values of σ have a smaller average for mixtures than for component grades.

The single comparison possible between results obtained with different discharges indicates that with mixtures, just as with their components, capacity increases with discharge in more than simple ratio.

MIXTURES OF MORE THAN TWO GRADES.

Experiments were made with a mixture of three grades, and with a mixture of five. The former was observed with discharges of 0.182 and 0.363 ft.³/sec., the latter with discharges of 0.182, 0.363, and 0.545 ft.³/sec. (See Tables 4 (J) and 60.)

Brief consideration only will be given to the data from the mixture of three, $(A_1C_1G_2)$, because the points on which they bear are more fully covered by the data from the mixture of five. Grades (A) and (C) differ from one another in fineness much less than either differs from grade (G). The triple mixture may therefore be thought of as half coarse and half fine, with the distinction that the fine half is made up of two grades. By comparing data from it with data from the closely related mixtures (A_1G_1) and (C_1G_1), in which the fine portion is of a single grade, we may throw light on the question whether the advantage to traction which is obtained by substituting two grades for one may be augmented by further diversification. With discharge 0.363 ft.³/sec. and slope 1.4 per cent the capacities for the three mixtures are

(A_1G_1)	$(A_1C_1G_2)$	(C_1G_1)
89	98	106

As the capacity for the triple mixture has a value midway between those for the two dual mixtures, no advantage is indicated for the greater diversification.

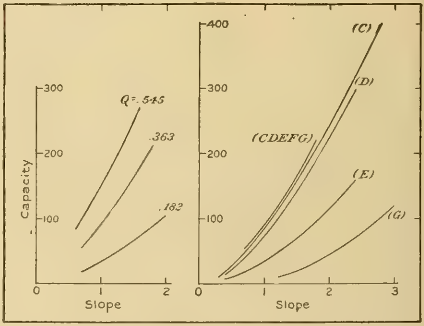

FIGURE 60.—Curves of capacity in relation to slope for a mixture of five grades, (CDEFG). Comparison of mixture curves for three discharges, and of mixture curve with curves for component grades.

In the mixture of five grades the proportions were so arranged as to approximate a natural combination. The components and their percentages are shown by writing $(C_{45}D_{35}E_{12}F_6G_2)$. The curves of capacity in relation to slope are shown, for the three discharges, in the left-hand diagram of figure 60. In the right-hand diagram the curve for discharge 0.363 ft.^{3}/sec. is repeated, and with it are placed the corresponding curves for four of the component grades—that for grade (F) being omitted because it is nearly coincident with the one for grade (E).

The curve for the mixture is not only of the same type with the others, but runs nearly parallel with those nearest. For all slopes the capacities obtained for the mixture are greater than for any component. The fact that the mixture gives a greater capacity than does the fine grade (C) alone shows that the addition to (C) of 35 per cent of (D) and 20 per cent of still coarser grades works an advantage instead of a detriment.

In figure 58 it is seen that the addition of 20 per cent of coarser débris to grade (B) increases capacity, and in figure 59 that a similar increase accompanies the addition of 20 per cent of coarser débris to grade (C). So far as the case of the more complex mixture is comparable to these, there is no indication that a mixture of great complexity has advantage for traction over a mixture of two components only. As to this point the inference from data of the five-part mixture is supported by that already drawn from a datum of the ($A_1C_1G_2$) mixture, and it is further supported by the facts brought together in the left-hand diagram of figure 61, which shows the capacity-slope curves of mixtures (C_4E_1) and (C_4G_1) along with that for the five-part mixture.

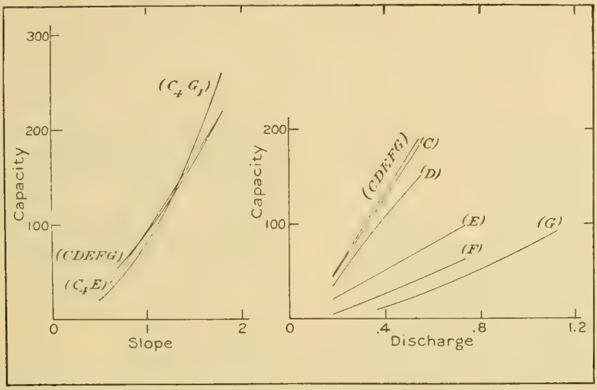

FIGURE 61.—Capacity-slope curves for related mixtures and capacity-discharge curves for mixture and component grades.

The right-hand diagram of figure 61 is a group of plots of capacity as a function of discharge. These plots pertain to the complex mixture and its five components, and all are conditioned by a slope of 1.2 per cent. They show that the tractional superiority of the mixture is not confined to the use of a particular discharge, and they indicate also that the capacity-discharge relation is essentially the same for the mixture as for separate grades. The locus of $C = f(Q)$ for the mixture is approximately a straight line, and if produced it intersects the axis of Q to the right of the origin. It might be expressed by an equation in the form of (64) with an exponent near unity.

A NATURAL GRADE.

Two series of experiments were made with an alluvium in its natural condition, except that the very finest constituents had been removed by passing it over a 60-mesh sieve. The observations are recorded in Table 4 (K), and the adjusted capacities in Table 60. In figure 62 the capacity-slope curves are plotted, and each is accompanied, for comparison, by the corresponding curves for grades (A) and (C).

The approximate mechanical analysis of this material, stated in terms of the separated grades of the laboratory series, is as follows:

	Per cent.		Per cent.
(A)	6	(D)	42
(B)	13	(E)	10
(C)	27	Coarser than (E)	2

The fact that the capacities (fig. 62) are greater than those for grade (C), notwithstanding the dominance of a component corresponding to the coarser grade (D), testifies again to the advantage for traction of a mixture as compared to a grade of narrow range in fineness.

It will be observed also that each of the curves from the natural grade resembles closely its neighbors from artificial grades. So far as their evidence goes the type is the same for both, and the tendency of their evidence is to show that the laws connecting capacity with slope, as developed by the study of sorted débris, apply also to unsorted stream alluvium.

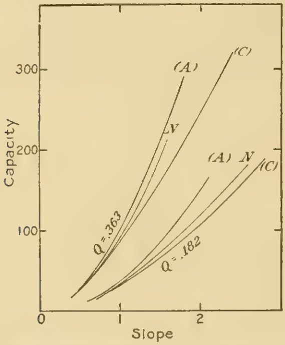

FIGURE 62.—Capacity-slope curves for a natural grade of débris, compared with curves for sieve-separated grades.

Table 63 (p. 180) gives computed finenesses for various mixtures and for this natural grade of débris. The fineness of the natural grade is nearly identical with that of grade (C), and the two thus afford a direct comparison between the capacities of a natural grade and a narrowly limited grade. For the same discharge and slope their tabulated capacities are respectively 168 and 143 gm./sec., the ratio of advantage to the natural grade being 1.17. The computed fineness of grade (CDEFG) does not correspond to that of any simple grade, but a comparison made by means of interpolation gives 150 and 131 gm./sec. as corresponding capacities for the mixture and a simple grade of the same mean fineness, and the ratio of the first to the second is 1.15. These ratios are smaller than those estimated from data for binary mixtures (p. 174), but are coordinate in value. The question of relative authority will be considered later.

CAUSES OF SUPERIOR MOBILITY OF MIXTURES.

When a finer grade of débris is added to a coarser the finer grains occupy interspaces among the coarser and thereby make the surface of the stream bed smoother. This quality of smoothness appealed to the eye during the progress of the experiments. One of the coarser grains, resting on a surface composed of its fellows, may sink so far into a hollow as not to be easily dislodged by the current, but when such hollows are partly filled by the smaller grains its position is higher and it can withstand less force of current. In other words, the larger particles are moved more readily on the smoother bed, and this fact also was a matter of direct visual observation. The promotion of mobility applies not only to the starting of the grain but to its continuance in motion. It encounters less resistance as it rolls or skips along the bed, and it is less apt to be arrested. When a single large particle travels along a bed composed wholly of grains much smaller it rarely leaps, but rolls instead, and it must in general be true that the larger particles in mixtures roll more and skip less than their smaller companions.

The admixture of finer débris thus changes the mode of traction for the coarser, and it is believed that the enhanced capacity is due mainly to this change. Capacity for the coarser is increased because the new condition reduces its resistance to the force of the current.

The fact that under some conditions the capacity for fine material is slightly increased by the addition of coarser is not so easily explained. The coarser grains do not make the bed smoother but rougher. The rougher bed retards the current. Even while rolling the larger grains are holding back the water, and the larger grains reduce the area of bed on which the traction of the smaller takes place. In these ways the presence of the coarse material tends to reduce the capacity of the current for the fine, and these factors certainly seem adequate to explain the general fact that capacity for the finer débris is reduced by admixture of the coarser.

Two factors may be named with the opposite tendency. The first is the impact of the coarser particles. In rolling and leaping they disturb the finer, tending thus to dislodge them from their resting places and either start them forward or else give them new positions from which they may be more easily swept. The second is the production of diversity in the current. Every obstruction diversifies the current. The deflection necessary to pass it both constitutes and causes diversity of direction, and diversity of direction necessitates diversity of velocity. If a pebble is placed on the sandy bed of a small stream, the transformation of the adjacent parts of the bed by the diversified current is obvious. The building up of the bed in the lee of the pebble testifies to lowered velocity, and the scouring at the side to heightened velocity. In the same way each coarser grain of a heterogeneous stream load diversifies the current about it and gives to such of the filaments as are accelerated greater power for the traction of finer grains. With reference to the transportation of the finer débris, the coarser grains have the function of obstructions whether they are partly embedded or lie on the surface or are rolled along.

If the factors concerned in the traction of the finer components of mixtures have been correctly stated, it is not difficult to understand that under most conditions the net result of their influences will be a reduction of capacity, and also that special conditions may determine an increase.

VOIDS.

The packing together of larger and smaller grains which tends toward a smooth stream bed tends also toward the reduction of interstitial spaces within the bedded débris, thus reducing the percentage of voids. It was suggested in the laboratory that the percentage of voids, used inversely, might serve as a sort of index of mobility, and estimates of the voids were accordingly made for most of the materials employed in the experiments with mixed grades. Partly for this purpose, and partly to obtain the factors needed to correct the weighings of load for interstitial water, a series of special weighings were made.

A vessel holding 535 cubic centimeters was filled with saturated débris and weighed. Afterward the same débris was weighed in a dry condition. The computation was made by the formula

$$\text{Percentage of voids} = \frac{W' - W}{535}$$

in which W' is the weight of saturated débris in grams and W the weight of dry débris.

Table 62 contains the estimated voids for the binary mixtures. In each series the percentages are smaller for the mixtures than for the component grades; and when the percentages were plotted in relation to the proportions of component grades (after the manner of the capacities in figs. 55 and 56) each series was found to indicate a minimum. The positions of the minima correspond to mixtures with 30 to 40 per cent of the finer grade of débris. In comparing voids with capacities, the minima of the void curves are to be considered in relation to the maxima of the capacity curves. Those maxima, however, are associated with mixtures having 60 to 90 per cent of the finer grade; and the attempt at correlation therefore fails. A single void curve is reproduced in figure 63, together with the corresponding capacity curve.

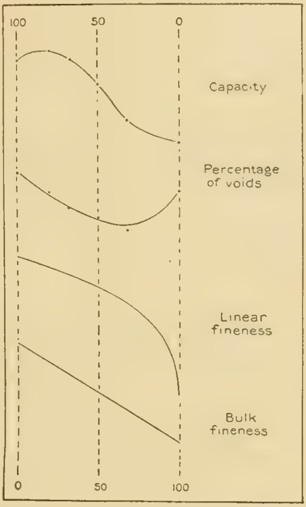

FIGURE 63.—Curves showing the relations of various quantities to the proportions of fine and coarse components in a mixture of two grades of débris, (C) and (G). The horizontal scale, when read from left to right, shows the percentage of the coarser component in the mixture.

TABLE 62.—*Percentages of voids in certain mixed grades of débris, compared with the percentages in the component grades.*

Percentage of finer grade in mixture.	Percentage of voids in grade—					
	(AC)	(AG)	(BF)	(CE)	(CG)	(EG)
0	44	38	37	40	38	38
20	....	28	31	33	....	....
33	....	24	29	32	26	29
50	40	29	29	33	30	28
67	....	31	34	35	33	34
80	...	37	39	37	38	36
100	44	44	46	44	44	40

FINENESS.

A similar attempt was made to correlate the capacity curves of figures 55 and 56 with fineness. In computing the fineness of a mixture, the finenesses of its components were used as data, and the combination was made with bulk finenesses (p. 21) as follows: Denoting the proportions of components by a, b, c, etc., their bulk finenesses by F_2', F_2'', F_2''', etc., and the fineness of the mixture by $F_2{}^m$,

$$F_2{}^m = \frac{aF_2' + bF_2'' + cF_2''' + \text{etc.}}{a + b + c + \text{etc.}} \quad \text{- - - -} (85)$$

Linear fineness, F, was then computed by formula (88).

The results are listed in Table 63, together with the corresponding capacities for traction when the discharge is 0.363 ft.^{3}/sec. and the slope is 1.4 per cent.

TABLE 63.—*Finenesses of mixed grades and their components.*

[Computed from data in Tables 1, 4 (J), and 4 (K).]

Grade.	$F_2\ 10^6$	F	C	Grade.	$F_2\ 10^6$	F	C
(A)	1,910	1,002	185	(C)	417	602	143
(A_1C_1)	1,163	848	161	(C_4G_1)	334	557	158
(C)	417	602	143	(C_2G_1)	278	526	144
				(C_1G_1)	209	478	106
				(C_1G_2)	139.3	418	50
(A)	1,910	1,002	185	(G)	0.451	61.8	16
(A_3G_1)	1,432	908	175				
(A_2G_1)	1,273	873	169				
(A_1G_1)	955	794	89	(E)	10.77	178	62
(A_1G_2)	637	678	42	(E_4G_1)	8.71	166	59
(A_1G_4)	420	604	25	(E_2G_1)	7.33	157	65
(G)	0.451	61.8	16	(E_1G_1)	5.61	143	49
				(E_1G_2)	3.89	127	33
				(G)	0.451	61.8	16
(B)	1,023	812	149				
(B_4F_1)	798	747	170				
(B_2F_1)	656	700	145	(A)	1,910	1,002	185
(B_1F_1)	482	632	129	$(A_1C_1G_2)$	582	673	98
(B_1F_2)	318	538	69	(C)	417	602	143
(B_1F_4)	186	459	39	(G)	0.451	61.8	16
(F)	1.685	95.9	33				
				(C)	417	602	143
(C)	417	602	143	$(CDEFG)$	228	492	150
(C_4E_1)	332	557	154	(D)	111.5	388	127
(C_2E_1)	275	524	135	(E)	10.77	178	62
(C_1E_1)	206	476	110	(F)	1.685	95.9	33
(C_1E_2)	137	406	91	(G)	0.451	61.8	16
(C_1E_4)	88	358	75				
(E)	10.77	178	62				
				Natural.	419	603	168

The comparisons of capacity with fineness for series of mixtures of two grades are illustrated by figure 63, where the horizontal scale is that of the proportions of fine and coarse in the mixture. The capacity curve is identical with the second in figure 55, and the other curves pertain to the same series of (C G) mixtures. The curves for capacity and linear fineness are strongly discordant, capacity changing most rapidly with mixtures approximately in the ratio of 1:1, and fineness changing most rapidly when the proportion of the finer grade is minute. The graph of bulk fineness is a straight line and betrays no sympathy with the sigmoid curve of capacity, though somewhat less discordant than the curve of linear fineness.

It is quite evident that the peculiar relation of capacity to the proportions of a binary mixture is not to be either accounted for or formulated as a relation of fineness, and we have just seen that it can not be formulated in terms of the percentage of voids. The elimination of those two associated factors leaves it—so far as our recognized alternatives are concerned—to be ascribed wholly to modifications of the texture of the channel bed and the consequent modifications of the mode of transportation, and to these factors it is not practicable to give numerical expression.

RELATION OF CAPACITY TO FINENESS, FOR NATURAL GRADES.

There is another way of comparing the capacities pertaining to mixed grades with the fineness of the grades, which largely avoids the influence of changing mode of traction and which throws a side light on the relation of capacity to fineness in the case of natural grades. Instead of comparing the data for different mixtures of the same two simple grades, it compares data from similar mixtures of different pairs of simple grades.

Figure 64 has been compiled from data in Table 63. Its upper group of five dots represents the logarithms of capacity in relation to the logarithms of linear fineness, for combinations of fine and coarse in the ratio of 4:1 (one ratio of 3:1 being included). The line drawn among them gives, by its inclination, an estimate of I_4, the synthetic index of capacity in relation to fineness, for a range in fineness from 166 to 908, the value being 0.70. The next group of dots corresponds to mixtures of two fine to one coarse and gives 0.57 as a value of the index. The next group, distinguished by crosses, corresponds to mixtures of one part fine with one of coarse. It includes six points, but one of these stands far from the line suggested by the others. The line, as drawn, represents an index value of 0.62. In the fourth group, distinguished by X's and corresponding to mixtures of one fine to two coarse, the points are so irregularly placed that no line can be drawn; and a fifth group, not reproduced, is equally irregular. Fineness seems to control capacity when the finer component of the mixture is the more important, but other factors mask its influence when the coarser component dominates.

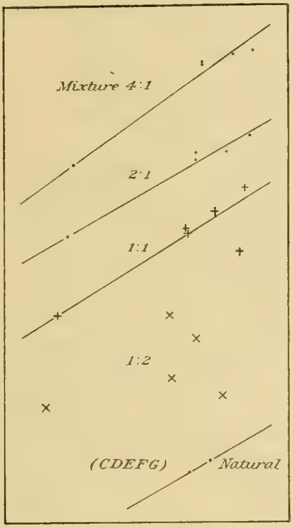

FIGURE 64.—Logarithmic plots of capacity in relation to linear fineness, for related mixtures of débris.

In preparing the mixture $(C_{45}D_{35}E_{12}F_6G_2)$ the endeavor was made so to apportion the components as to approximate a natural grade. To whatever extent that effort succeeded, the data obtained with use of the mixture are comparable with those afterward obtained with a natural grade. The capacities and finenesses of the complex mixture and the natural grade are represented by two plotted points near the bottom of figure 64, and the line drawn through them gives 0.57 as a value of the index. Unfortunately the range in fineness covered by the two is small—from 492 to 603—so that their determination of I_4 has little weight; its close agreement with other values may be largely accidental.

In Table 45 mean values of I_4 based on work with the sieve-separated grades are so arranged as to show their control by slope, discharge, and trough width. On making the indicated allowances for differences in condition, and comparing those values with the values indicated by figure 64, it appears that the latter are somewhat smaller but that the differences are not great. The index values from data of the experiments with mixtures range from 0.57 to 0.70. Coordinate values from the experiments with single, sieve-separated grades would range from 0.70 to 0.90.

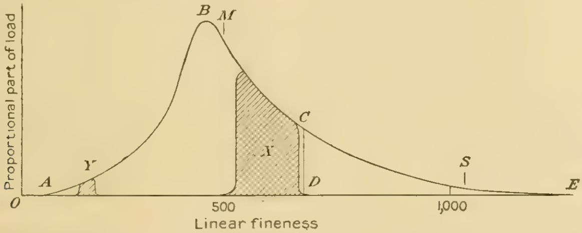

FIGURE 65.—Curve illustrating the range and distribution of finenesses in natural and artificial grades of débris.

In considering the bearings of these estimates there is advantage in giving graphic expression to the conditions they severally represent. When the results of mechanical analyses of sands and similar materials are presented graphically, the usual practice is to plot integrated quantities, or proportions, of ingredients on a scale of fineness or coarseness; but for the present purpose it is convenient to use the quantities without integration. In figure 65 the horizontal scale is that of linear fineness, and the ordinates are relative quantities of components of different finenesses. The curve *ABC* represents the composition of the débris constituting the tractional load of a river and is based on a sample of alluvium from a river bed. The area *ABCD*, between the curve and the axis of fineness, represents the total load and corresponds to the 100 per cent of integrative diagrams. The range in fineness is limited at *A* by competent fineness for traction, coarser material on the river bed not being moved by the particular discharge to which the diagram corresponds. It is limited in the opposite direction by competent fineness for suspension, the area *CED* representing suspendible material entangled with the bed load. The mean fineness of the tractional load is marked at *M*.

In sorting débris for the laboratory experiments, the material of the river's load was divided by sieves, and this partition might be represented in the diagram by a series of vertical lines—slightly flexed to take account of the influence on the separation of irregularity in shape of particles. The shaded areas *X* and *Y* may represent the constitution as to fineness of two of the sieve-separated grades.

The experiments show that for a narrowly limited grade, such as *X* or *Y*, which has the same mean fineness as the river alluvium, *ABCD*, the capacity for traction is much less than for the alluvium. They indicate also, though less decisively, that for a nearly equal mixture of a fine grade with a coarse, both being narrowly limited, the capacity is nearly the same as for the unsorted alluvium, provided the mean fineness is the same. The essential property appears to be abundance of both coarse and fine, and not multiplicity of grades of fineness.

Passing now from capacity to capacity's rate of variation—in respect to fineness—or to the valuation of i_4, we find a certain parallelism. For the narrowly limited grades the sensitiveness of capacity to fineness, as measured by the index i_4, extends upward from about 0.60; while values of the synthetic index, I_4, range from 0.70 to 1.00 or more. As to these values the data are not abundant. For mixtures of two narrow grades we have a few estimates of I_4, of which the largest is 0.70; and for grades similar to *ABCD* a single weak estimate of 0.57. If we conclude that the sensitiveness of capacity to fineness is less for natural grades than for the narrowly limited grades, we must base the inference almost wholly on the data from the mixtures of two grades, connecting the latter with natural grades by aid of the analogy outlined above. This I am willing to do, but at the same time I would record my recognition of the weakness of the evidence and reasoning. It is estimated that, on the average, the capacity of streams for natural grades of débris varies with the 0.60 to 0.75 power of linear fineness. This is equivalent to saying that capacity varies with the 0.20 to 0.25 power of bulk fineness, or with the fifth or fourth root of bulk fineness.

While the curve in figure 65 is based on the mechanical analysis of material which constituted the tractional load of a river current, there is no reason to believe that its form presents a dominant type. Inspection of other analyses, in fact, suggests that such curves exhibit much variety and may sometimes even present two maxima. The load which a natural current carries is determined not only by the two limits of competence, but by the character of the material within its reach. Neighboring affluents of a river may bring to it strongly contrasted grades of débris, or their tribute may at one time be much finer than at another. Moreover, a river is not a simple current, but a complex of currents, which vary in competence and in the character of their loads. It is true that, the channel being considered as a whole, its load at one point is essentially the same as just above or just below, but the mode of movement involves a continual remodeling of the bed and a sorting and re-sorting of the material. The load at any particular point and time is conditioned by many factors of the complex. For this reason a representative sample of a river's load is not easy to define or to collect.

In view of this complexity it is difficult to apply even a simple formula to problems in river engineering, and refinement in formulation would be of little avail. For the same reason it is not practicable to derive a formula directly from river data, and the product of the laboratory is the best available, despite the artificial simplicity of its conditions.

DEFINITION AND MEASUREMENT OF MEAN FINENESS.

The term "mean fineness," as here used, is not free from the possibility of misapprehension. As the fineness of débris is a property depending on the size of component particles, it is not unnatural to think of fineness as a property of the particles—and there is, for that matter, a fineness of particles. To obtain the mean fineness of particles, one would first determine the finenesses of the individual particles, and then the mean of those finenesses. The basal unit would be the particle. In deriving the mean fineness of a body of débris the basal unit is some unit by which quantity of débris is measured. It may be a unit of weight or a unit of volume. In this report a body of débris is conceived to be composed of equal volume units, each of which has a determined or determinable fineness, and its mean fineness is the mean of the finenesses of the volume units. In dealing with bulk fineness the mean computed is the arithmetical mean of the finenesses of units. In dealing with linear fineness the mean computed is the cube root of the arithmetical mean of the cubes of the finenesses of units.

The intricacy of the definition of mean linear fineness arises from the relation of linear fineness to bulk fineness. The fundamental concept is that of bulk fineness, and the definition of linear fineness rests upon it. Linear fineness is essentially a derivative of bulk fineness, and mean linear fineness is an exactly similar derivative of mean bulk fineness. To pass from an assemblage of linear finenesses to their mean, it is necessary to pass through bulk fineness, and that passage involves cubes and cube root.

Bulk fineness is defined as the number of particles in a unit volume (1 cubic foot), it being assumed there are no voids. It is the reciprocal of the volume of the particle—which might be called bulk coarseness. There are two practical modes of measuring it. If the specific gravity of the débris be known (or assumed), measurement includes a weighing and a counting. Then, W being the weight, N the number of particles, G the specific gravity, W_0 the weight of a cubic foot of water, and F_2 the bulk fineness,

$$F_2 = \frac{W_0 G N}{W} \text{ - - - - - - - - - - - - } (86)$$

If the specific gravity be not known, measurement includes two weighings and a counting. Then, W being the weight in air and W_1 the weight in water,

$$F_2 = \frac{W_0 N}{W_1 - W} \text{ - - - - - - - - - - - - } (87)$$

This procedure determines bulk fineness when all particles have the same volume; when they are of different volumes it determines mean bulk fineness. As a matter of fact, all our measurements in the laboratory were of mean fineness. It is not possible by any method of sorting with which I am acquainted to separate from a natural alluvium a grade which is really uniform in fineness.

When the mean fineness of a sample of débris is desired, there is no need to separate it into grades, because the process for measuring the mean fineness of the whole is identical with that for measuring the fineness of a grade, When bodies of débris of known finenesses are mingled, the mean fineness of the mixture is computed by a formula (85), which sums the finenesses by unit volumes (or weights) and then divides by the number of unit volumes.

Linear fineness is defined as the reciprocal of the mean diameter of the particles of the débris. Like bulk fineness, it is treated as a property of the body of débris and not as a property of the particle. Mean diameter is defined as the diameter of a sphere having the same volume as the particle. Defined thus, linear fineness is a function of volume of particle, and as bulk fineness is also a function of that volume, the two have a fixed relation:

$$F = \left(\frac{\pi}{6}\right)^{\frac{1}{3}} F_2^{\frac{1}{3}} \text{ - - - - - - - - - } (88)$$

Substituting in (88) from (86) and (87), we have

$$F = \left(\frac{\pi}{6}\right)^{\frac{1}{3}} \left(\frac{W_0 G N}{W}\right)^{\frac{1}{3}} \text{ - - - - - - } (89)$$

$$F = \left(\frac{\pi}{6}\right)^{\frac{1}{3}} \left(\frac{W_0 N}{W_1 - W}\right)^{\frac{1}{3}} \text{ - - - - - - - - } (90)$$

The computations of fineness for this report used (89) or (90); or, what is equivalent, they first determined bulk fineness by (86) or (87), and then derived linear fineness by (88). The computations of mean linear fineness applied (88) to mean bulk fineness.

It would have been possible to formulate fineness in such a way that the definition of linear fineness would be direct and comparatively simple, but any such formulation would encounter complexity in some of its parts, provided it established a logical relation between linear fineness and bulk fineness. Its adoption would also involve the sacrifice of simplicity in the measurement of fineness. Any system requiring the direct measurement of diameters would be inferior for practical purposes to the one here used.

The subject of scales of fineness has been elaborated because nearly all the results as to the control of capacity by fineness would be quite different if a different scale were used. If, for example, mean linear fineness had been defined as the arithmetical mean of linear finenesses, the curve for linear fineness in figure 63 would be a straight line, while the line for bulk fineness would be a curve similar to that shown for linear fineness but turned through 180°.

When the fineness of the tractional load of a stream is to be determined by means of a sample of the débris constituting its bed, account must be taken of another factor. Omitting considerations affecting the selection of a sample, which belong to Chapter XIII, let us assume that the sample in hand is representative of the stream's tractional load. In addition to the débris which was carried along the bed, it inevitably includes finer material which was carried in suspension. Suspended particles are arrested along with the coarser and form part of every stream deposit. Once lodged in the interstices of coarser particles, they are sheltered from the current and are not again disturbed so long as the coarser material remains. If the deposition of the coarser débris is very rapid the amount of entangled finer stuff may be small, but when deposition is slow the interstices act continuously as traps and catch suspendible débris until they are filled. The latter is the usual condition, and the tractional sample therefore ordinarily contains a considerable percentage of suspensional material. To separate the two it is necessary to draw an arbitrary line, for the graduation in fineness is complete. As regards interstitial space, the tractional part of the sample is comparable with the more complex mixtures of the laboratory, and its voids may be estimated as 25 per cent of the whole space. The suspensional débris packed in these voids may be assumed itself to include 25 per cent of voids, so that the net volume of its particles is three-fourths that of the containing voids, or 18.75 per cent of the whole space. The net volume of the tractional particles being 75 per cent of the whole space, the two divisions of the sample bear the relation, by net volume or by weight, of 75 to 18.75, or of 4 to 1. This gives a practical rule for separation. The sample should be divided, with aid of sieves and scales, into a coarser four-fifths and a finer one-fifth, and only the coarser part should be used in estimating mean fineness. In figure 65 the entrapped suspensional material is represented by the triangular area *CDE*.

SUMMARY.

The purpose of the experiments with mixtures was to bring the results from work with separate grades into proper relation with phenomena of unsorted natural material. The indications given by these experiments are in part direct and in part conditioned by the principle adopted in framing a scale of fineness. The adopted principle makes the conception of bulk fineness fundamental and that of linear fineness derivative.

The capacities for traction observed in the experiments with narrowly limited grades are less than for equivalent grades with greater diversity in fineness. A study of data from mixtures of two narrow grades indicates that the ratio of advantage for diversified débris is from 1.17 to 2.22, the mean of five estimates, from different groups of data, being 1.66. Two comparisons of results from highly diversified grades, with results from nearly homogeneous grades of the same fineness, give as estimates of the ratio of advantage 1.15 and 1.17. The larger estimates were made by an indirect method but are independent of the scale of fineness. The smaller estimates were made by a direct method but involve the theory of the scale of fineness. In combining the two groups of estimates, greater weight is assigned to the smaller, not because they are of recognized higher authority, but because the same scale of fineness will almost necessarily be used in applying the results of the investigation to practical questions. The compromise value of 1.2 is adopted, as a correction to be applied to values of capacity in Table 12 in estimating capacities for diversified grades of like fineness.

The advantage of diversification appears to arise largely from the fact that the finer particles, by filling spaces between the coarser, make a smoother road for the travel of the coarser, and it is not proved that a highly diversified débris gives higher capacity than one containing only two sizes of particles.

It is especially notable that when fine material is added to a previously homogeneous coarse material not only is the total capacity increased, but the capacity for the coarser part of the load is increased, and it may even be enlarged several fold. The general effect of adding coarse to fine is to reduce the stream's capacity for the fine, but under some conditions there is a slight increase.

The general relations of capacity to slope, discharge, and fineness (and presumably to form ratio also) are the same for natural and other complex grades of débris as for the sieve-sorted grades of the laboratory, but some of the constants are not quite the same.

The sensitiveness of capacity to slope is on the average the same for both classes of débris grades, but the variation of sensitiveness in relation to slope, as determined by the constant σ, is somewhat less for natural grades.

As to the relation of capacity to discharge comparison was limited to a single example, and that suggested no modification of the constants derived from work with laboratory grades.

The sensitiveness of capacity to fineness is somewhat less for natural grades than for the the laboratory grades. No values of the constant ϕ were obtained for complex grades, and comparisons of sensitiveness were made only by means of the synthetic index of relative variation. The average value of that index, for natural grades of débris transported under laboratory conditions, is estimated at 0.20 to 0.25 for bulk fineness.

CHAPTER X.—REVIEW OF CONTROLS OF CAPACITY.

INTRODUCTION.

In the preceding seven chapters the relations of capacity for stream traction to a variety of factors have been examined one at a time. It is now proposed to bring together some of the discovered elements of control. The experimental data thus far considered pertain to straight channels, and the factors of control connected with bending channels have not received attention. Those factors must be included when the attempt is made to bring laboratory results into relation with river phenomena, but as they constitute a category by themselves it is convenient to leave them out of the account in correlating the results from straight-channel work.

The immediate determinants of capacity are (1) the velocities of the current adjacent to the channel bed, (2) the widths of channel bed through which those velocities are effective in moving débris, and (3) the mobility of the débris constituting the bed and the load. It was not found practicable to measure bed velocity, but measurement was applied to its two chief determinants, slope and discharge, and also to its intimate associate, mean velocity, and these have been discussed separately. Width has entered into the discussion chiefly as an associate of depth in the determination of form ratio. By reason of these and other interrelations the six controls of capacity which have been discussed—slope, discharge, fineness, depth, mean velocity, and form ratio—are not independent, and not all should appear in a general equation. Slope, discharge, and fineness being accepted as of primary importance, it is feasible to add but one of the others, and choice has been made of form ratio.

FORMULATION BASED ON COMPETENCE.

The functions used in discussing the relations of capacity to slope, discharge, and fineness are similar, and each involves a conception of competence. Competence enters also the theory of the relation of capacity to form ratio, but it enters in a different way. It is convenient to omit at first the form-ratio function and consider together the three which are similar. They are:

$$C=b_1(S-\sigma)^n \text{-----------} (10)$$

$$C=b_3(Q-\kappa)^o \text{-----------} (64)$$

$$C=b_4(F-\phi)^p \text{-----------} (75)$$

Each of these equations expresses the law of variation of capacity with respect to one condition when the other two conditions are constant, and in that sense they are independent; but there is a mutual dependence of parameters which is of so complete a character that they are essentially simultaneous. The dependence of parameters is more readily stated by means of a specific instance than in general terms. In equation (10) b_1, σ, and n are constant so long as Q and F hold the same values; they do not vary with variation of S. But when the values of Q and F are changed those of b_1, σ, and n are modified. Through this control of its parameters the equation involves the relation of capacity to discharge and fineness.

The coefficient b_1 is the value of capacity when $(S-\sigma)=1$; b_3 when $(Q-\kappa)=1$; b_4 when $(F-\phi)=1$. Replacing them by b_5, as the numerical value of capacity when $(S-\sigma)=1$, $(Q-\kappa)=1$, and $(F-\phi)=1$, we may combine the three equations into

$$C=b_5\ (S-\sigma)^n\ (Q-\kappa)^o\ (F-\phi)^p \text{----} (91)$$

The constant b_5 is not of the same unit with either b_1, b_3, or b_4. Its dimensions, derived from those of the variables of (91), are $L^{3p-3o}M^{+1}T^{o-1}$.

From the experimental data have been computed 92 values of n, 20 values of o, and 5 values of p. (See Tables 15, 32, and 44.) All these are positive. The following statistical summary gives a general idea of their relative magnitudes. Its figures are not based on the same range of observational data; but the ranges for o and p correspond approximately with the middle part of the range for n.

Exponent.	Number of determinations.	Mean value.	Range of values.
n	92	1. 59	0. 93–2. 37
o	20	1. 02	. 81 -1. 24
p	5	. 58	. 50– . 62

It will be recalled that while the forms of the equations involving σ, κ, and ϕ were based on the conception of competence, it was not found possible to correlate those parameters strictly with competent slope, discharge, and fineness. The correlations were obstructed by phenomena of dune rhythms and of diversified fineness and could not be completed, but the forms of equation were found to be well adapted to the combined expression of observational data above the region of competence. Their relation to competence is not absolute but intimate, and it is so intimate that certain properties of the parameters may properly be inferred from the physical theory of competence.

When the swiftest velocity on the bed is barely able to move débris, there is a threefold condition of competence. For the particular discharge and fineness, the slope is competent; for the particular slope and fineness, the discharge is competent; for the particular slope and discharge, the fineness is competent. The conditions of competence for the three factors controlling capacity are thus not only similar but simultaneous and coincident. Neither factor can sink alone to the limiting level of competence, but the three arrive together. This is an important principle and lies at the foundation of the systematic interdependence of parameters and variables.

$$\left.\begin{array}{l}\text{In equation (91) the quantities}\\ \quad (S-\sigma),\ (Q-\kappa),\text{ and }(F-\phi)\text{ be-}\\ \quad\text{come zero simultaneously. When}\\ \quad S=\sigma,\text{ then also }Q=\kappa,\text{ and }F=\phi;\\ \quad\text{and vice versa.}\end{array}\right\}\text{......}(92)$$

As capacity varies directly with $(S-\sigma)$, $(Q-\kappa)$, and $(F-\phi)$, it is also true that each of these varies directly with capacity. Any change of condition which affects capacity affects those three quantities in the same sense. For example, suppose discharge to be increased. This not only increases $(Q-\kappa)$ and thereby increases capacity, but it also increases $(S-\sigma)$ and $(F-\phi)$. One mode of expressing this fact is to say that capacity measures the remoteness of each controlling factor from the initial status of competence, and all recede or approach together.

Let us now make a more definite assumption, that discharge is increased while slope and fineness remain the same. The resulting increase of $(S-\sigma)$, as S is unchanged, implies a diminution of σ; and the increase of $(F-\phi)$ implies a diminution of ϕ. That is, σ and ϕ vary inversely with discharge. Parallel reasoning shows that σ and κ vary inversely with fineness, and that κ and ϕ vary inversely with slope.

These relations are here developed deductively from the theory of competence. They have been developed inductively from the observational data, for equations (26), (66), and (77) include

$$\left.\begin{array}{l}\sigma=f\,(\grave{Q},\ \grave{F})\\ \kappa=f_{I}\,(\grave{S},\ \grave{F})\\ \phi=f_{II}\,(\grave{S},\grave{Q})\end{array}\right\}\text{...........}(93)$$

No way has been found in which to study the exponents deductively. The only evidences of order discovered by comparison of observational data pertain to n, which has been found (equation 27) to vary inversely with discharge and fineness. The question whether o and p follow similar trends could not be answered by the adjusted data because of the cumulative effect of accidental errors. There is, however, considerable force in analogic reasoning, based not only on equations (93), but on other elements of symmetry in the relations of capacity to the several factors—elements to be noted later. The state of the evidence may be expressed by

$$\left.\begin{array}{l}n\ =f_{III}(\grave{Q},\ \grave{F})\\ {[o\ =f_{IV}(\grave{S},\ \grave{F})]}\\ {[p\ =f_{V}\,(\grave{S},\ \grave{Q})]}\end{array}\right\}\text{...........}(94)$$

It is convenient to have a name for the group of constants designated by Greek letters, and as they define the conditions of competence, they may be called *competence constants.*

The exponent n and the associated competence constant σ, as they vary with Q and F

and do not vary with S, are controlled by Q and F. As they both vary inversely with Q and with F, it follows that they vary directly one with the other. It is evidently true in general that each exponent varies directly with the associated competence constant.

$$\left.\begin{array}{l} n=f_{VI}(\acute{\sigma}) \\ o=f_{VII}(\acute{\kappa}) \\ p=f_{VIII}(\acute{\phi}) \end{array}\right\}\text{- - - - - - - - - - - - -}(95)$$

With σ constant, the variation of $S-\sigma$ is determined by variation of S. Considered as additive, their variations are identical; but if we regard the changes as ratios, the changes in $(S-\sigma)$ are proportional to $\frac{1}{S-\sigma}$ and those in S to $\frac{1}{S}$. The ratio between these fractions, which is $\frac{S}{S-\sigma}$, is a measure of the sensitiveness of $(S-\sigma)$ to changes in S. It is evident that as S increases the sensitiveness diminishes. As capacity varies with a power of $(S-\sigma)$, the sensitiveness of capacity to slope becomes less as the slope increases.

Any change in S causes, according to (92) and (93), a change of opposite character in κ and o. When S is increased, κ and o are reduced. As the sensitiveness of $(Q-\kappa)$ to change in Q is measured by $\frac{Q}{Q-\kappa}$, it is evident that the reduction of κ lessens the sensitiveness. This has the effect also of lessening the sensitiveness of capacity to discharge; and that sensitiveness is further lessened by the reduction of o. Parity of reasoning shows that increase of slope lessens the sensitiveness of capacity to fineness, so that the effect of increasing slope is to reduce the sensitiveness of capacity to all three of its controlling factors. It is evident also that a similar result would be reached if the analysis began by assuming an increase of discharge or fineness.

It is a general principle that any change in one of the control factors, slope, discharge, and fineness, causing capacity to increase, has the effect also of making capacity less sensitive to changes in each and all of the control factors; and the inverse proposition is of course equally true. The statement being phrased to include both, the sensitiveness of capacity to the three controlling conditions varies inversely with capacity.

The term "sensitiveness," as used in the preceding paragraphs, is equivalent to the more specific "index to relative variation," for which the symbol i has been used; and by reference to various studies of the control of the index by conditions it may be seen that the entire scope of the general principle just stated has been covered by essentially inductive generalizations. From equations (39), (68), and (79),

$$\left.\begin{array}{l} i_1=f_{IX}(\grave{S},\ \grave{Q},\ \grave{F}) \\ i_3=f_{X}\ (\grave{S},\ \grave{Q},\ \grave{F}) \\ i_4=f_{XI}(\grave{S},\ \grave{Q},\ \grave{F}) \end{array}\right\}\text{- - - - - - - - - - -}(96)$$

This checking of deductive by inductive results helps to establish the second and third equations of (94), which were inferred from analogies.

Very little is known of the nature of the functions in (93) to (96), beyond the fact that those of (95) are increasing and the others decreasing. Deductive reasoning has not been successfully applied, and induction has escaped the entanglement of accidental errors in only a single instance and to a limited extent. The exceptional instance is that represented by the first equation of group (96). The symbols being translated into words, that equation reads: The index of relative variation for capacity in relation to slope varies inversely with slope, with discharge, and with fineness. There are in fact three distinct propositions, and each of these might be expressed by a separate equation. As to the first proposition, that the index varies inversely with slope, it was found, inductively, that the rate at which it varies with slope is itself a decreasing function of slope and also of discharge and fineness; and knowledge of similar character was gained as to the second and third propositions (pp. 104–108). Representing by di_{1S}, di_{1Q}, and di_{1F} the rates of variation of the index in relation to slope, discharge, and fineness, severally, we have

$$\left.\begin{array}{l} di_{1S}=f_1(\grave{S},\ \grave{Q},\ \grave{F}) \\ di_{1Q}=f_2(\grave{Q},\ \grave{F}) \\ di_{1F}=f_3(\grave{F}) \end{array}\right\}\text{- - - - - - - - - -}(97)$$

These fragmentary determinations are all of one tenor, and in view of the remarkable symmetries already discovered among the elements of equation (91), they render probable the general proposition:

The rate at which capacity varies inversely with each of the three controlling conditions, slope, discharge, and fineness, itself varies inversely with each of the conditions. (98)

Returning to (92) and (93), we may indicate certain corollaries.

Starting from the status of competence, let us assume that slope is increased, with destruction of the status, and that the status is restored by reducing discharge. In the restored status σ is greater than in the original, κ is less, and ϕ is unchanged. It is evident that the nature of the result does not depend on the particular assumptions, and that we may pass to the general proposition:

When capacity is zero, the competence constants are so related that a change in any one of them involves a change of contrary sign in some other. (99)

Starting from a status characterized by a particular value of capacity, we may first break it by increasing slope and then restore it by decreasing discharge (fineness remaining unchanged). The first change reduces κ and ϕ; the second increases σ and ϕ. It does not appear whether the net result for ϕ involves change in its value, but if so the change is probably small in relation to the increase in σ and the decrease in κ. It is evident that the nature of the result does not depend on the particular assumption, and that we may pass to two general propositions, each of which includes (99) as a special case:

Under the condition that capacity is constant, the competence constants are so related that a change in any one of them involves a change of contrary sign in some other. (100)

Under the condition that capacit is constant, the values of slope, discharge and fineness are so related that a change in any one of them involves a change of contrary sign in some other. (101)

It follows also that

Under the condition that capacity is constant, the value of each controlling condition (S, Q, or F) is so related to the corresponding competence constant (σ, κ, or ϕ) that the two vary in same sense. (102)

Propositions (100) and (102) are deduced from equations (93). By parity of reasoning equations (94) yield (103) and (104), but these two propositions share whatever uncertainty attaches to (94).

Under the condition that capacity is constant, the exponents n, o, p are so related that a change in any one of them involves a change of contrary sign in some other. (103)

Under the condition that capacity is constant, the value of each controlling condition (S, Q, or F) is so related to the corresponding exponent (n, o, or p) that the two vary in the same sense. (104)

As capacity can not be increased under (91) without increasing S, Q, or F, and as the increase of one of these involves under (93) the decrease of two competence constants, without any change of the third, it follows that the competence constants, collectively, vary ininversely with capacity. The same reasoning, if applied to (91) and (94), yields a similar conclusion as to the exponents. To combine the two in a single statement:

The competence constants σ, κ, and ϕ, taken as a group, and the exponents n, o, and p, taken as a group, vary inversely with capacity. (105)

I find it not easy to bring into combination the laws of internal relation between parameters of a group and the laws which connect the groups with capacity; but if these laws be regarded as conditions, it is possible to frame more comprehensive theorems of tentative character. Equations (106) are of this class and are thought worthy of examination, although the data at hand do not suffice for their testing.

$$\left.\begin{array}{l} f_1(\acute{\sigma})+f_2(\acute{\kappa})+f_3(\acute{\phi})-f_4(\grave{C})=0 \\ f_5(\acute{n})+f_6(\acute{o})+f_7(\acute{p})-f_8(\grave{C})=0 \end{array}\right\} \text{- - - -} \quad (106)$$

The equation under discussion,

$$C=b_5(S-\sigma)^n(Q-\kappa)^o(F-\phi)^p \text{- - - - - -} \quad (91)$$

is an expression of relation between capacity and three of its controls, namely, slope (S), discharge (Q), and fineness (F). It involves seven parameters, of which six are functions of the independent variables, S, Q, and F. It is thus a bare framework, and the completion of the structure calls for the replacement of the six parameters by their values in terms of the variables. The laws contained in the equations and propositions numbered (92) to (98), with their corollaries, (99) to (105), are contributions toward the completion of the structure, but they are largely of the nature of restrictions. They impose conditions to be satisfied by the perfected equation.

Some of the conditions are already embodied in the form of (91), and with reference to such conditions it is important that the origin of that form be not overlooked. The form assumes that the three competence constants are the values of the corresponding variables when capacity is zero, whereas their identification with those values is by no means complete. The definition and recognition of the status of competence are so obstructed by the complicating conditions of nonhomogeneous débris and dune rhythm that no more can be asserted than an indefinitely representative relation. For most purposes, however, we are little concerned with conditions in the immediate neighborhood of the competence limit, so that this qualification is of small practical moment. Outside of the neighborhood of competence the support of the form is empiric; it has served well as a scheme for the marshaling of the observations. The support is qualified, in turn, by the fact that the observations are not of such harmony and precision as to discriminate nicely among formulas of adjustment. In view of these qualifications, the possibility has been recognized that some of the laws above enumerated might emanate from the form of the equation and have no other basis; and in view of this possibility the foundations of each conclusion have been scrutinized. I believe that all the inferred laws, from (92) to (105), are essentially inductive.

It is easy to understand that any constructive effort which should hang all supplementary conditions on the framework of (91) would result in a formula so unwieldly as to be useless. It is a matter of faith with me that if our data were so precise as to substitute definite quantitative relations for the fascicle of trends and indefinite parallelisms they have actually furnished, some way would be found leading from complexity to simplicity. I am not without hope that the presentation here made may suggest to the mechanist, familiar with the aspects of solved problems of similar difficulty, a rational theory under which the data may advantageously be recombined.

In an effort to discover unities among the complexities of the capacity relations, equation (91) was given the following form:

$$\frac{C}{b_5}=\sigma^n\kappa^o\phi^p\left(\frac{S}{\sigma}-1\right)^n\left(\frac{Q}{\kappa}-1\right)^o\left(\frac{F}{\phi}-1\right)^p \text{- -} (108)$$

The three factors making the second division of the second member, being independent of the units of measurement, seemed well adapted to the expression of comprehensive harmonies, if such exist.

The following negations were demonstrated:

The quantities $\frac{S}{\sigma}$, $\frac{Q}{\kappa}$, and $\frac{F}{\phi}$ are not equal, nor are the ratios between them constant.

The quantities $\frac{S}{\sigma}-1$, $\frac{Q}{\kappa}-1$, and $\frac{F}{\phi}-1$ are not equal, nor are the ratios between them constant.

The quantities $\left(\frac{S}{\sigma}-1\right)^n$, $\left(\frac{Q}{\kappa}-1\right)^o$, and $\left(\frac{F}{\phi}-1\right)^p$ are not equal, nor are the ratios between them constant.

It was also found that the symmetric factors in equation (91), namely, $(S-\sigma)^n$, $(Q-\kappa)^o$, and $(F-\phi)^p$, are not equal, nor are the ratios between them constant.

THE FORM-RATIO FACTOR.

In its relation to form ratio capacity has two zeros, one corresponding to a high ratio, the other to a low. Each of these corresponds also to a competent bed velocity, so that into a perfect formula competence would enter twice. The formula adopted, however, ignores the element of competence, chiefly because its recognition, which would add a complication, was not seen to be of advantage for the expression of the control of capacity in the more important regions outside the vicinity of competence. The accepted formula is

$$C=b_2\left(1-\frac{m}{m+1}\cdot\frac{R}{\rho}\right)R^m \text{ - - - - - - - } (58)$$

The quantity ρ is that value of R which corresponds to the maximum value of C—the maximum standing between the two zeros—and b_2 is a capacity constant. The function as a whole qualifies capacity by means of a numerical factor and may be combined with (91) by multiplication of the factors:

$$C=b(S-\sigma)^n(Q-\kappa)^o(F-\phi)^p\left(1-\frac{m}{m+1}\cdot\frac{R}{\rho}\right)R^m \text{ - - - - - - - - - - - - - - - - } (109)$$

The coefficient b, replacing b_5 and b_2, is a quantity of the same unit with b_5 (see p. 186), but numerically independent.

The function now added is of distinct type from the others, for instead of advancing by a continuous law from zero to infinity it first rises to a finite maximum and then returns to zero. The first three factors are harmonious; the fourth discordant. At every stage in the investigation the discussion of the laboratory data has been hampered by this discordance. In order to treat adequately the relation of capacity to either slope, discharge, or fineness, it was necessary to isolate that relation by equalizing other conditions, and slope or discharge or fineness could readily be equalized; but the form-ratio factor was intractable. By means of interpolation it was possible to assemble varied data characterized by the same form ratio, but that did not meet the difficulty. It was necessary to take account of the relation of the particular ratio to the optimum ratio, ρ; and the value of ρ varies with all other conditions.

The sensitiveness of capacity to form ratio, as measured by the index of relative variation, is less than its sensitiveness to other conditions. The average of 48 values tabulated in Chapter IV is 0.24, while similar averages for fineness, discharge, and slope are three, five, and seven times as great. The distribution of sensitiveness, in relation to values of the independent variables, is illustrated by figure 66, where four curves are plotted, each representing a particular instance, selected as typical. The vertical scale is the same for all; and the ordinates represent values of the index of relative variation. The horizontal scale is that of slope for the curve SS, of discharge for the curve QQ, of fineness for the curve FF, and of form ratio for the curve $R\rho R$. The vertical cc represents the competence constants and is an asymptote to three of the curves. The horizontal line mm gives the value of the exponent m corresponding to the form-ratio index. For values of R greater than ρ the index is negative, but its curve is drawn above the zero line to represent sensitiveness, which is not affected by sign.

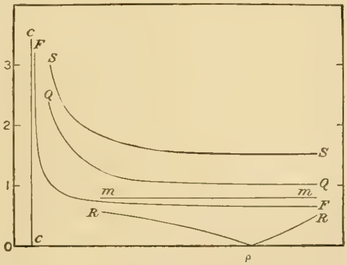

FIGURE 66.—Typical curves illustrating the distribution of the sensitiveness of capacity for traction to various controlling conditions. Ordinates represent values of the index of relative variation; abscissas, to four different scales, represent values of slope, discharge, linear fineness, and form ratio.

The two parameters of the form-ratio factor have laws of variation similar to those of the other parameters; each varies inversely with values of all independent variables except its own.

$$\rho=f\,(\grave{S},\grave{Q},\grave{F}) \text{ - - - - - - - - - - } (61)$$

$$m=f\,(\grave{S},\grave{Q},\grave{F}) \text{ - - - - - - - - - - } (62)$$

It follows that each varies directly with each of the other parameters (σ, κ, ϕ, n, o, and p).

The relations of the parameters to form ratio are less simple. In all cases the evidence from the observational data is conflicting, and as the several cases have come up for consideration the trend of evidence has seemed now in one direction and now in another. Impressions as to those trends are recorded in the preceding chapters, but when assembled they fail to indicate any general principle. Recourse is therefore had to theoretic considerations alone, and the conclusions reached can claim no direct support from the tabulated values of exponents and competence constants.

The conclusion (105) that the competence constants collectively vary inversely with capacity is based on the fact that individually they vary inversely with things which promote capacity, namely, slope, discharge, and fineness. Let us now assume that those three conditions remain constant and consider the effect of varying form ratio. Initially let the form ratio be so small that the bed velocity is competent; σ, κ, and ϕ are severally equal to the competent values of S, Q, and F. Now change width and depth so as to increase the form ratio and capacity becomes finite. That capacity may be finite, σ, κ, and ϕ must be less than S, Q, and F, and as the latter have not changed the competence constants have been reduced by the increase of form ratio. By parity of reasoning it can be shown that if the initial form ratio be so large as to make the bed velocity competent a reduction of form ratio will cause a reduction of σ, κ, and ϕ. Somewhere between the two form ratios of competence lies ρ, the form ratio of maximum capacity, and between the same limits lie minimum values of the competence constants.

The greater the capacity induced by adjustment of form ratio, the greater the reduction of slope, for example, necessary to reduce capacity to zero, and as this reduction varies directly with the depression of σ below the initial value of S, it follows that the minimum value of σ (and similarly of κ and ϕ) coincides with the maximum of capacity.

The conclusion that the competence constants vary inversely with capacity is therefore true for the case in which changes in capacity are caused by changes in form ratio. It can be shown also that the exponents, n, o, and p, follow the same law.

The extension of this principle to the domain of form ratio gives assurance that the conclusions embodied in equations and propositions (99) to (108), conclusions which were reached from phenomena of slope, discharge, and fineness, are not vitiated by the traversing phenomena of form ratio.

The function in the form-ratio factor of (109) being characterized by a maximum, the variations of parameters with respect to form ratio are characterized by a minimum. This law may be so combined with those of (93), (94) (61), and (62) as to yield the following system of equations for the trends of changes in parameters consequent on changes in the four independent variables of equation (109):

$$\left.\begin{array}{ll}\sigma = f_1\,(\grave{Q},\ \grave{F},\ \breve{R}) & n = f_5\,(\grave{Q},\ \grave{F},\ \breve{R}) \\ \kappa = f_2\,(\grave{S},\ \grave{F},\ \breve{R}) & o = f_6\,(\grave{S},\ \grave{F},\ \breve{R}) \\ \phi = f_3\,(\grave{S},\ \grave{Q},\ \breve{R}) & p = f_7\,(\grave{S},\ \grave{Q},\ \breve{R}) \\ \rho = f_4\,(\grave{S},\ \grave{Q},\ \grave{F}) & m = f_8\,(\grave{S},\ \grave{Q},\ \grave{F})\end{array}\right\} \quad (110)$$

In the development of the form-ratio factor of equations (58) and (109), detailed in Chapter IV, the factor first appeared as $(1-\alpha R)R^m$, the quantity α being a numerical coefficient introduced to represent the resistance to the current occasioned by the sides of the channel. It was afterward shown that $\alpha = \frac{m}{m+1}\,\frac{1}{\rho}$, and that form of coefficient was substituted. These relations show that either α or m varies in value with the character and amount of the resistance by the channel sides; and, in point of fact, both do. Nor is that control restricted to the parameters of form ratio. Lateral resistance affects also, and in comparable degree, the parameters of slope, discharge, fineness, and capacity. The sides of the laboratory channels were vertical and were of wood, planed and painted. Had they been smoother or rougher, or had they been inclined, the whole system of values given by the experiments would have been different. There is no reason, however, to question that they would have yielded the same qualitative results.

DUTY AND EFFICIENCY.

The discussions of duty and efficiency in Chapters III and V give reason for the belief that the variations of either quantity in relation to controlling conditions may advantageously be expressed by an equation identical in form with (109). Such an equation would not be interconvertible with (109), nor would an equation for duty be the exact equivalent of one for efficiency. By the aid of reasonable assumptions the parameters of either equation might be derived from the parameters of another, but the results of computations by the several equations would not be strictly compatible. These discordances may be demonstrated as properties of the algebraic forms.

They are also connected with the fact that the algebraic forms imperfectly represent the physical phenomena. It is possible that the physical facts are closely represented by some one of the equations, in which case the incompatibilities of the other two equations are wholly of the nature of errors; but if this be so, our data do not enable us to indicate the truer equation.

The exponent in the slope factor is greater for the capacity and duty equations than for the efficiency equation, the difference being a large fraction of unity. The exponent in the discharge factor is greater for the capacity equation than for those of duty and efficiency, the difference being a large fraction of unity. The competence constant in the slope factor is smaller in the capacity and duty equations than in that for efficiency, the difference being a small fraction of the constant. The competence constant in the discharge factor is smaller for the capacity equation than for the others, the difference being relatively large. The interrelations of parameters and the relations of parameters to independent variables are qualitatively the same for the equations of duty and efficiency as for the equation of capacity.

THE FORMULA OF LECHALAS.

THE FORMULA.

The only earlier serious attempt to formulate the transportation of débris, so far as I am informed, is that of C. Lechalas, who wrote in 1871, under the title "Note sur les rivières à fond de sable."[1] His discussion makes use of Dubuat's experiments on competent velocity (1786), Darcy and Bazin's formulas for velocities in conduits and rivers (1878), and observational data accumulated by the French engineering corps in connection with projects for the improvement of navigable rivers. In the following abstract of the more elementary part of his discussion the symbolic notation and the terminology of the present paper are to some extent substituted for those of the original.

Postulate a stream of fixed width and constant discharge, traversing a bed of uniform sand, unlimited in quantity but without accessions. So long as the velocity along the bed exceeds a certain value the current transports sand. Below that limit the sand is undisturbed.

The discharge, Q, and width, w, being known, the mean depth, d, the slope, s, the mean velocity, V_m, and the bed velocity, V_b, are given by the following three equations, of which (1) and (3) are from Darcy and Bazin. The constants are in meters.

$$\frac{ds}{V_m} = 0.00028 + \frac{0.00033}{d} \qquad (1)$$

$$Q = wdV_m \qquad (2)$$

$$V_b = V_m - 10\sqrt{ds} \qquad (3)$$

The sand travels (1) by rolling, (2) by suspension. A particle of water impinging on the bottom gives motion to a sand grain, the motion having a direction which depends on the impact and on the positions of adjoining particles, solid and liquid. The grain is projected free from the bottom or is rolled along it, the particular result depending on the inclination and force of the impact and on various conditions which affect the resistance. Suspension corresponds especially to impacts associated with high velocities. Suspension is rare below a certain critical velocity for each density and size of sand grain. Transportation is slow at low stages of a variable stream, rapid and by suspension at high stages. The grains describe trajectories analogous to those of the water particles, but shorter; and there are frequent returns to the bottom, as well as restings between excursions. Larger grains are lifted less high, or are rolled only, or remain at rest. Small grains afford a better hold (prise) in relation to their weight. The smallest of all are carried in the body of the current.

The amount by which the pressure on the upstream face of a grain immersed in a current exceeds the pressure on the downstream face is proportional to the square of the velocity. Represent it by aV_b^2, the coefficient a depending on size, form, and position. For the sand of the Loire, the resistance developed equals $a\,0.25^2$, as that sand is immobile when $V_b < 0.25$. "The difference is equal to the product of the mass of the grains by their velocity, projected on the same axis as V_b—that is to say, on the axis of the stream. This product, being proportional to the discharge [load] of sand, C, may be represented by the expression hC. We have then:

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[1] Annales des ponts et chaussées, Mém. et doc., 5th ser., vol. 1, pp. 381-431, 1871.

$$C=\frac{a}{h}\left(V_b^2-0.25^2\right)=m\left(V_b^2-0.06\right) \quad (4)$$

The value of the m will be sought from observation, which will correct in a measure for the introduction of V_b into the equation without allowance for the speed of the grains, etc. Subtraction of 0.06 ceases when the sands are prevented by suspension from rubbing on the bottom; therefore the formula becomes $C=mV_b^2$ for velocities above a certain limit. (It is readily understood that m, like a, is only approximately constant.)"

The rate at which dunes advance has been measured, in the French rivers, in relation to the velocities of the associated currents. It rises with V_b until the critical velocity is reached, and then drops as the change is made from rolling to suspension. The advance of dunes, depending on the fall of grains into the eddy (fig. 10) when they have been rolled to the crest, is affected by the introduction of suspension because then only a part of the traveling grains are received by the eddy.

Observations made on the Loire give as the limiting bed velocity for transportation [competent velocity for transportation], $V_{bc}=0.25$ meters per second. According to an engineer who has discussed those observations [H. L. Partiot ?], the corresponding surface velocity, V_s, is equal to $\sqrt{0.11}$; and the formula for the rate of advance of the dunes,

$$\text{Rate of advance}=0.00013\ (V_s^2-0.11) \quad (5)$$

is good for all values of V_s up to 1.016. One might base on this a formula for load in relation to surface velocity, but the formula would be incomplete unless developed so as to take account of the depth; and it is best for the present to adhere to equation (4), which connects load with bed velocity.

Lechalas, however, for a temporary purpose, uses formulas of Darcy and Bazin to connect V_b with V_s, under certain assumptions as to depth, and with their aid computes for the Loire the critical bed velocity, V_{bcc}, at which suspension of the sands begins. $V_{bcc}=0.55$ meters per second. This is the velocity corresponding to $V_s=1.016$, the surface velocity which limits the applicability of formula (5).

The following table contains the observational data on dunes of the Loire and compares the observed rates of dune advance with rates computed by formula (5).

TABLE 63a.—*Data on subaqueous dunes of the Loire.*

Surface velocity.	Height of dunes.	Rate of dune advance.	
		Observed.	Computed.
Met./sec.	*Meters.*	*Met./sec.* × 10^{-5}	*Met./sec.* × 10^{-5}
0.58	0.900	3.0	3.0
.64	.300	3.3	3.9
.73	.300	5.1	5.5
.75	.782	6.3	5.9
.81	.967	6.7	7.1
.81	.967	7.5	7.1
.83	.760	7.6	7.5
1.00	.953	10.5	11.6
1.016	.920	12.4	12.0
1.016	.580	12.0	12.0
1.03	.487	6.2	12.35
1.05	.612	7.0	12.9
1.11	1.198	5.8	14.6
1.13	.650	8.7	15.2
1.33	.950	5.6	21.6

In later passages Lechalas recognizes the variations of velocity in passing from one vertical to another of the same stream section and makes (4) the formula for a division, one unit wide, of the cross section. Thus modified, it is applied in a variety of ways to practical engineering problems of the Loire.

DISCUSSION.

Lechalas's classification of transportation processes differs from that adopted for our work in that he makes saltation, at least verbally, a part of suspension. I am led, however, by a study of the more detailed descriptions of his colleague Partiot, to believe that the line practically drawn between rolling and suspension differs in small measure only from the line we have drawn between traction and suspension.

The lower critical velocity of Lechalas is the exact equivalent of our velocity competent for traction, and his upper critical velocity corresponds approximately to our velocity competent for suspension. The two attempts at formulation likewise agree in giving prominence to the factor of competence. They differ in the mode of using that factor, and they are actuated by different preconceptions.

In the first sentence of the passage (pp. 193–194) which has been inclosed in quotation marks to indicate its literal translation, Lechalas appears to equate the velocity of a particle of the load with the difference between the forward pressure of the current and the resistance given by the particle. Hooker[1] suggests that the acceleration of the particle instead of its velocity is intended; but with or without such emendation the author's reasoning is obscure to me, for I see no necessary physical relation between the number or mass of débris particles moved and the pressure of the current. The load may be defined as the product of the mass of particles by their average speed; and their speed, being produced by the pressure of the current, may be simply related to it, but any relation of the mass to the pressure is necessarily indirect and presumably involved.

Whatever the strength or weakness of the postulates on which the formula is based, the manner in which it incorporates the principle of competence gives it a rough resemblance to those we have developed, while the characterization of its constant *m* gives to it a large empiric factor; and it is in order to inquire whether, as an empiric formula, it finds support in the Berkeley data. As the Berkeley observations do not include bed velocities, the most direct comparison is impracticable; but an indirect relation may readily be established.

The difficulty we have found in defining bed velocity may be avoided, for the purpose of the present comparison, by accepting the definition used by Lechalas in

$$V_b = V_m - 10\sqrt{ds} \quad \text{----------} \quad (3)$$

and by assuming depth to be constant. According to the Chezy formula this assumption makes V_m approximately proportional to $\sqrt{s}$, so that $10\sqrt{ds}$, in (3), is proportional to V_m. It follows that V_b is proportional to V_m, and this permits us to substitute V_m for V_b in equation (4) by changing the constants:

$$C = K(V_m^2 - k) \quad \text{----------} \quad (6)$$

This expression implies that capacity for traction varies with mean velocity at a rate which diminishes as mean velocity increases but is never so low as that of the second power of mean velocity. The corresponding data from our experiments, namely, the data for capacity in relation to mean velocity under the condition of constant depth, are in accord with this, except that they indicate a limiting index of relative variation somewhat less than 2. In Table 51 the values of the synthetic index, I_{vd}, range from 2.03 to 7.86; and a value of 2.03 for the synthetic index implies smaller values of the instantaneous index. This discrepancy is not important, and the formula of Lechalas, regarded as empirical, is probably adequate for the discussion of a body of observations on capacity and velocity. It could not, however, be used in connection with the Berkeley data unless both *K* and *k* (or *m* and 0.06 in equation (4)) were permitted to vary with conditions.

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[1] Hooker, E. H., Am. Soc. Civil Eng. Trans., vol. 36, p. 256, 1896.

CHAPTER XI.—EXPERIMENTS WITH CROOKED CHANNELS.

EXPERIMENTS.

In order to study the influence which bends in the channel exert on capacity for traction, a short series of experiments were made with channels having angular bends and others with channels having curved bends. Each of these channels had a width of 1 foot and was shaped by means of partitions within a trough 1.96 feet wide. (See fig. 67.) Above and below the bends were straight reaches of the same width. All the experiments were made with débris of grade (C) and with a discharge of 0.363 ft.^{3}/sec. The loads were measured. In some experiments the head lost in the region of the bends was measured by means of level readings on the water surface above and below.

After each experiment the profile of the bed was determined by levelings at intervals of 1 foot, and in several cases the region of the bends was covered by such levelings and sketches as to make it possible to construct a contour map of the bed.

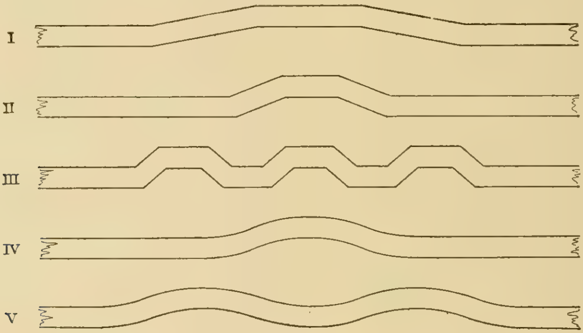

FIGURE 67.—Plans of troughs used in experiments to show the influence of bends on traction.

SLOPE DETERMINATIONS.

The profiles of the channel beds as shaped by the current were plotted. Through that part of the profile corresponding to the straight channel above the bends was drawn a straight line representing the mean slope for that region, and a similar straight line was drawn below the region of the bends. From a point on the first line near the position of the first bend to a point on the second line corresponding to a position several feet below the last bend a straight line was drawn, and this was assumed to represent the mean slope of the channel in the region affected most by the bends. The profiles above the bends showed evidence of the rhythms commonly observed in the straight-channel experiments. The profiles below the bends showed steeper undulations, which were ascribed to the influence of the strong agitation of the water in passing the bends. In estimating the slopes in the region of the bends the distance used was the length of the medial line of the channel.

The observations for head were made at points 2 feet and 4 feet above the first bend and 3 feet and 5 feet below the last bend, and the slopes were computed for the distances, on the medial line, between the points.

Check estimates of slope for straight channels were obtained by interpolation from Table 12, the determinations of load being used as arguments.

The data are assembled in Table 64, where the stronger and weaker determinations of the slope of the débris surface are severally indicated by the letters *a* and *b*. The measurements of water slope are thought to be coordinate in value with those of débris slope. The slopes computed from load measurements are probably of less weight.

Table 64.—*Comparison of slopes required for straight and crooked channels, respectively, under identical conditions of discharge, fineness, width, and load.*

[Débris of grade (C); discharge, 0.363 ft.^{3} sec.; width, 1 foot.]

Shape of crooked channel. (See fig. 67.)	Load.	Slope in straight channel.		Slope in crooked channel.	
		Computed from load by Table 12.	Profile of débris above first bend.	Average slope of débris.	Average slope of water surface.
	Gm. sec.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
I.......	19	0.42	0.30 *b*	0.45 *b*	0.46
	75	.92	.89 *b*	.89 *a*	.93
	56	.77	.74 *b*	.80 *a*	.78
II......	60	.80	.70 *a*	.81 *b*	.72
III.....	61	.82	.94 *b*	1.15 *a*	....
IV......	60	.80	.76 *a*	.80 *a*	....
	60	.80	.85 *a*	.85 *b*	....
V.......	63	.83	.72 *b*	.83 *b*	....
	63	.83	.62 *b*	.80 *b*	....
	66	.85	.87 *b*	.81 *a*	....
	64	.84	.87 *a*	.77 *a*	....
	64	.84	.86 *a*	.80 *a*	....

Note.—Values marked *a* are given greater weight than those marked *b*.

FORMS AND SLOPES.

The combinations of bends in the experiment channels are shown in figure 67. In three of the channels the bends were angular; in two curved. In channel I the angle of deflection was 10.5°; there was a single group of four bends, returning the course to its original direction; and the short reaches were approximately 5 feet long. In channel II the arrangement was the same, with reaches of about 2.5 feet and deflection angles of 21.5°. In channel III were three groups of four deflections each, the angles being of 40.9° and the length of reach about 1.4 feet. Channel IV had the same proportions as No. II, with the substitution of curves for angles. The radius of curvature for the medial line was 6.55 feet. Channel V contained two groups of curves, each similar to the group in No. IV.

From the data (Table 64) connected with channels I, II, and III, it appears that with angular bends a greater slope is necessary to transport the load than when the channel is straight—that is, the capacity is reduced by angular bends. The reduction is greatest when the angle of deflection is greatest, and it is so small for an angle of 10° as to leave doubt whether it might not disappear altogether with a somewhat smaller angle.

The single group of curves (IV) appears to reduce capacity slightly (increase of slope for same load): but the double group (V) gives slopes indicating an increase of capacity.

As the bends of alluvial streams are curved, the curved experiment channels may be assumed to represent them better than do the angular channels, and it is possible that meandering channels have a greater capacity for traction than straight channels of the same length. There are, however, certain elements of incompleteness in the representation which make definite inference hazardous. The course of a stream which shapes its own channel through an alluvial plain is made up of bends and reaches. In passing from reach to bend there is a gradual increase of curvature until the radius of curvature, for the medial line, is between twice and three times the width of the channel, and the change from bend to reach is also gradual. The forms are automatically adjusted to the system of accelerations and velocities within the current. The angular change of direction in the bend may be one of a few degrees only, but in meandering streams it is commonly from 90° to 180°. In the artificial channels all curves were circular arcs with a radius of 6.55 times the channel width; there was no graduation in the radial acceleration due to deflection; the change from right-hand deflection to left-hand deflection was abrupt, without the intervention of a reach, and the changes of direction were through angles of 21.5° and 43°. That such differences are competent to affect transportation to a material extent is indicated by the relations of deeps and shoals (crossings) to bends. Fargue,[1] from a discussion of an artificially adjusted portion of the Garonne, reached the conclusion that the distance downstream from the apex of a curve to the deepest point of the associated deep and the distance downstream from a point of inflection to the associated crossing are each normally one-fourth the length of a stream unit—defined as the portion between two points of inflection. In our experiments (see fig. 68) each of these distances is one-half the length of the stream unit instead of one-fourth.

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[1] Fargue, L., La forme du lit des rivières à fond mobile, Paris, 1908.

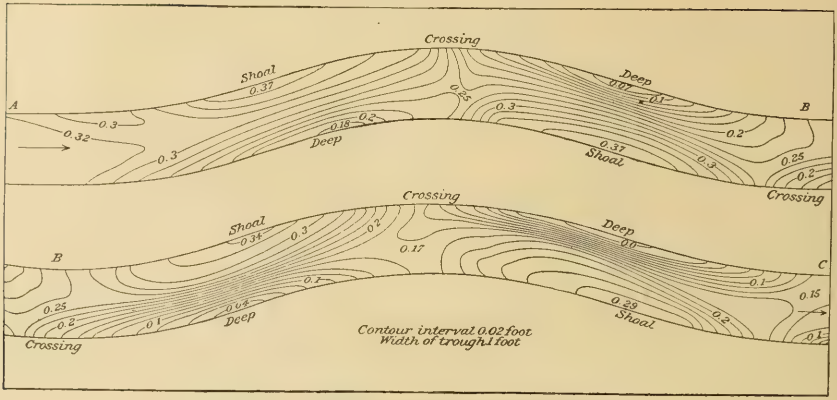


FIGURE 68.—Contoured plot of a stream bed, as shaped by a current.

In view of these facts, the apparent results of the experiments with crooked channels must be received with caution, and probably nothing more should be claimed for them than a general indication that the capacity of a moderately bent channel does not differ greatly from that of a straight channel.

FEATURES CAUSED BY CURVATURE.

Incidentally the experiments illustrated several consequences of curvature in addition to the influence on slope and capacity. At each turn the swiftest part of the current was thrown to the outer or concave side of the channel, and the slower parts moved toward the opposite side, the transfers giving to the current as a whole a twisting motion. The action on the débris became exceptionally strong near the outer side and exceptionally weak near the inner. A result of the strong action was that part of the load was thrown upward, so as to be temporarily suspended, and a result of the diversity of velocity was the maintenance of deep places near the outer wall and of shoals near the inner. Associated with the twisting motion were many whirls or eddies; and the general obliquity of motion had the effect of reducing the mean velocity in the direction of the general flow. The reduction of mean velocity was recorded in an increase of mean depth, which amounted, in the average of all examples, to 7 per cent and ranged from 2 to 14 per cent.

CHAPTER XII.—FLUME TRACTION.

THE OBSERVATIONS.

SCOPE.

That which distinguishes flume traction from stream traction is the fixity of the channel bed. In stream traction the shapes of the bed are adjusted to the rhythms of the mode of transportation, and its texture is that of the débris in transit. In flume traction the bed is unresponsive, but its texture, being independently determined, has an important influence on the mode of transportation. The experiments were arranged to determine the influences of different textures of bed on mode of traction and capacity for traction and were otherwise varied in respect to slope, width, discharge, and the character of débris transported.

GRADES OF DÉBRIS.

The material transported in the experiments included most of the grades already described (see Table 1 and Plate II) and also several mixtures not previously mentioned. In order conveniently to show the relations of the mixtures to their components, all the grades of débris used in the flume experiments are listed below in Table 65, the data of Table 1 being repeated so far as necessary. The elements of the table are defined at page 21. The material of the coarse grades (I) and (J) differs from that of the finer, being about 2 per cent less dense. Its particles also are somewhat less thoroughly rounded, their journey from the parent rock bed having been short.

TABLE 65.—*Grades of débris.*

Grade name.	Sieves used in separation (meshes to 1 inch).	*D.*	*F.*	F_2.
		Mean diameter of particles (foot).	Number of particles to linear foot.	Number of particles to cubic foot.
(B)	40–50	0.00123	812	1,023,000,000
(C)	30–40	.00166	602	417,000,000
(E)	10–20	.00561	178	10,770,000
(G)	4–6	.0162	61.8	451,000
(H)	3–4	.0230	43.4	156,000
(I)	1–2	.0547	18.3	11,900
(J)	½–1	.110	9.1	1,440
(E_1G_1)		.00698	143.2	5,610,000
($E_2H_1I_2$)		.00706	141.7	5,430,000
($E_3H_2I_3J_2$)		.00836	119.6	3,266,000

APPARATUS AND METHODS.

The experiment trough, a modification of that represented in the frontispiece, was 60 feet long and 1.91 feet wide, with vertical sides. The sides and bottom were of wood, planed and painted. For a portion of the experiments the bottom was covered by a false bottom, specially prepared to present a definite character of roughness, the sides remaining smooth. The trough was so arranged that it could be given various determinate slopes up to 3 per cent, and by means of an inclined false bottom a slope of 4.5 per cent was made. By means of a partition the width was reduced, for the greater part of the work, to 1.00 foot.

The width of trough at the outfall end was regulated by a contractor, as described on page 25. The débris was delivered at the outfall to a settling tank, which had two divisions; and a deflecting apparatus was so arranged that the delivery could be instantaneously diverted from one division to the other.

Above the trough near its head was a sloping platform on which measured units of débris were dumped at regular intervals, determined by a watch, and from which the débris was fed to the current by hand, with the aid of a scraper. The rate of feed was modified by changing the interval between dumpings, and by successive trials it was adjusted to the capacity of the current.

In accelerating the débris, as it fell into the water, the current was retarded, so that close to the feeding station it was slower than elsewhere. When the load was approximately adjusted to the general capacity of the current it constituted an overload in this particular tract, with the result that a portion was deposited. The load would then traverse an upper division of its course on a bed of débris, while in the lower and principal division it was in direct contact with the bottom of the trough. A tendency of the stream of débris to clog near the upper end of the trough, although moving freely beyond, was the ordinary criterion of the proper adjustment of the feed, and when this condition existed the load delivered at the outfall was assumed to represent the capacity of the stream. The outfall was then directed for a measured interval of time to a reserved division of the settling tank, and the débris thus separately received was weighed.

Besides the deposit connected with the feeding of débris there were transitory deposits of a rhythmic character, as described later.

Five characters of channel bed were used, namely, a planed and painted wood surface; a rough-sawn, unplaned wood surface; a surface of wood blocks, with grain vertical; a pavement of sand grains, set in cement; and a pavement of pebbles. (See Pl. III.)

PROCESSES OF FLUME TRACTION.

MOVEMENT OF INDIVIDUAL PARTICLES.

Flume traction differs from stream traction in its extensive substitution of rolling for saltation and in the important place it gives to sliding. The relative importance of these modes of particle movement is determined (1) by the texture of the bed surface in relation to the size of the particle, (2) by the velocity of the water in relation to the size of the particle, and (3) by the shape of the particle.

In stream traction the order of roughness of the bed is given by the fineness or coarseness of the material of the load, and this fact determines saltation as the dominant process. In flume traction the bed may be much smoother. On a smooth stream bed any particle with a broad facet is apt to slide, and a well-rounded particle to roll. Rolling is determined (rather than sliding) not only by the fact that the propulsive force of the current and the resistance given by the bed constitute a couple, but also by the fact that the current applies a greater force to the upper part of the particle than to the lower. The less smooth the bed surface, the greater its resistance and the more effective the couple in causing the particle to roll. With any particular texture of bed, the sizes of particles may determine their modes of progress, the largest sliding, those of smaller size rolling, and the smallest leaping. Increase of velocity tends to increase saltation at the expense of rolling and to increase rolling at the expense of sliding.

A particle rolled slowly is in continuous contact with the bed. A round particle may roll rapidly on a smooth bed without parting from it. Roughness of the bed causes changes of direction in the vertical plane, and such changes combined with high velocity cause leaps. If the particle is not round its rolling involves rise and fall of the center of mass, and such changes combined with high velocity cause leaps. Shape of particle may thus be a determinant between saltation and rolling, as well as between rolling and sliding.

A flattish particle, which may either slide or roll, travels faster when rolling. This is due partly to the fact that when it rolls it rolls on edge and thus projects farther into the current, and partly to the fact that the resistance at contact with the bed is greater for sliding than for rolling. It is also true that rolling particles as a class outstrip sliding particles as a class, the difference in speed being marked.

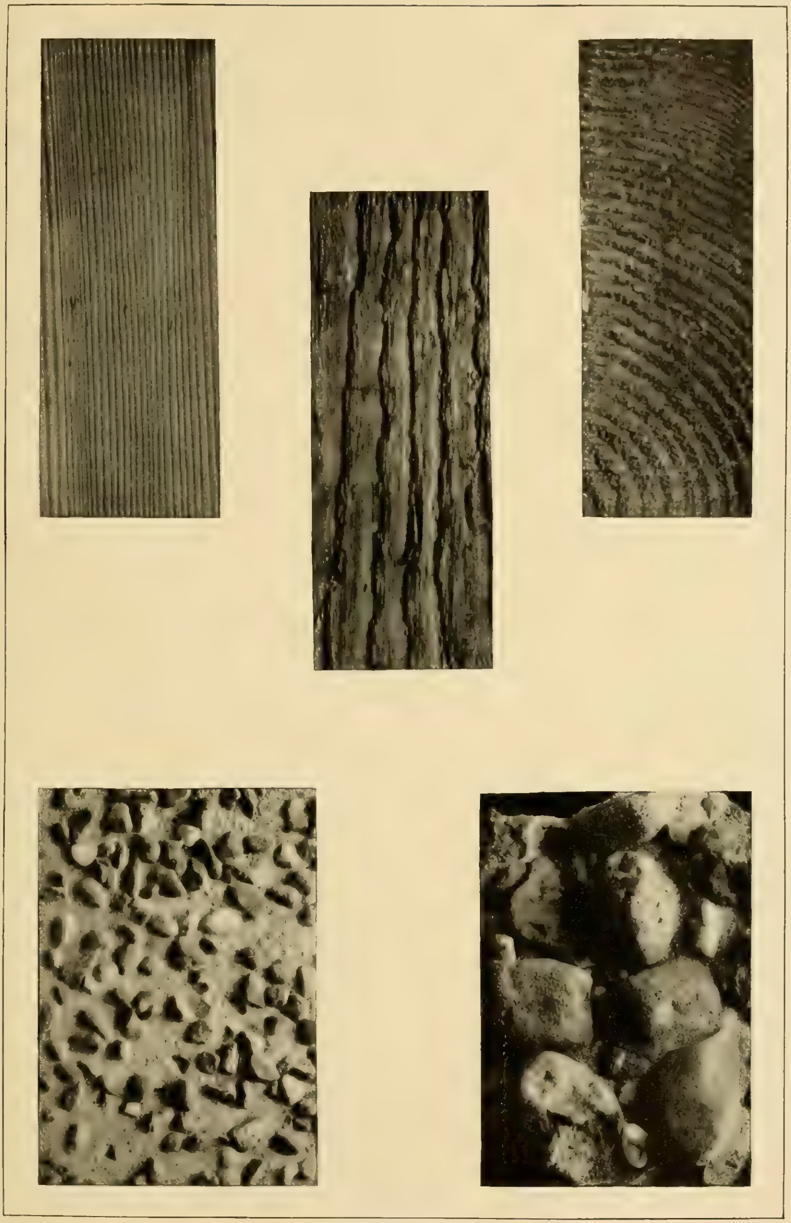
For particles of similar size those which dominantly roll outstrip those which dominantly leap. This is part of a more general fact that the better-rounded particles travel faster than the more angular. In the traction of mixed débris, where rolling is characteristic of larger particles and saltation of smaller, the larger travel faster than the smaller. There are thus two important ways in which rolling gives greater speed than saltation. It was not learned whether a particle which alternately rolls and leaps travels faster in one way than in the other.

A suspended particle, having the same speed as the water, outstrips all others. It is therefore possible that as saltation approaches the borderland of suspension its speed exceeds that of rolling.

When samples of different grades are fed to the same current in succession, it is found that the coarser travel the faster, whatever the mode of progression (except suspension). In the following record of experiments the speeds of grade (J) constitute an apparent exception, but their slowness is ascribed to the fact that the particles of that grade were relatively angular.

Table 66.—*Relative speeds of coarse and fine débris in flume traction.*

Depth of water.	Mean velocity of water.	Average speed of débris particles.		
		Grade (E).	Grade (H).	Grade (J).
Foot.	*Ft./sec.*	*Ft./sec.*	*Ft./sec.*	*Ft./sec.*
0.127	4.35	3.2	3.9	3.8
.182	3.04	2.3	2.4	....
.110	2.52	1.85	2.0	2.0
.182	1.52	.70	.85	....



ROUGH SURFACES USED IN EXPERIMENTS ON FLUME TRACTION.

It may be observed in passing that the recorded speed of the particles is on the average 75 per cent of the mean velocity of the water, the ratio being greater as the velocity is greater and as the depth is less. A higher ratio would of course be found if the speed of particles were to be compared with that of the lower part of the current. The percentage might be less than 75 if the stream were fully loaded.

In watching the traction of mixed débris it was observed, as already mentioned, that the larger particles traveled faster than the smaller. As it is difficult in such an observation to avoid giving attention largely to the more active particles, the observation applies especially to those which roll, but there is probably a similar contrast between the speeds of less active particles also. In an experiment with glass balls of different sizes it was found that the larger were rolled by the current somewhat faster than the smaller.

In attempting to understand the more rapid propulsion of the larger particles it is natural to compare the phenomenon with the more familiar fact that in the absence of water a large stone or ball will descend an incline with greater speed than a small one, but there is an important difference between the two cases. The object descending a dry incline is impelled by gravity, acting directly, and part of the resistance comes from the fluid in which it is immersed, whereas the rolling débris pebble is impelled chiefly by the moving fluid which surrounds it. The advantage in speed accruing to the larger pebble in flume traction is probably connected with the fact that the velocities of the current increase from the bottom upward. If the velocities were all the same the pressures applied to similar pebbles of different diameter would be proportional to their sectional areas, or to the squares of their diameters; but because of the gradation of velocities the increase of pressure in consequence of increase of diameter is more rapid than the increase of the square of the diameter. The chief resistance to the forward movement of the pebble is engendered at its contact with the bed and is of the nature of rolling resistance. For uniform speed, the rolling resistance of a wheel is proportional to its downward pressure divided by its diameter; and since in the case of the pebble the pressure is proportional to the cube of the diameter, the rolling resistance is proportional to the square. Increase in size of the rolling pebble is thus accompanied by increase of both propulsive force and rolling resistance, the increment to propulsive force being somewhat the larger; and the equality of force and resistance is restored by an increase of speed, which has the effect of reducing the propulsive force and increasing the resistance.[1] The reduction of propulsive force is connected with the fact that that force is determined at each instant by the velocities of the water, not as referred to the fixed bed, but as referred to the moving pebble.

The analysis of forces might be further developed, but the foregoing brief outline serves to indicate a mechanical principle underlying the observed fact that a current rolls large particles more swiftly than small. The principle is of fundamental importance in accounting for certain contrasts between the laws of flume traction and those of stream traction.

The discrimination of traction and suspension, usually easy in the experiments with stream transportation, was difficult in the flume work. The zone of saltation grew deeper with progressive increase of slope until it occupied the whole depth of the stream. Further increase of slope, with increase of load, made the cloud of particles denser, but there seemed no way of telling when the condition became that of a flowing mixture of water and sand.

COLLECTIVE MOVEMENT.

To the general fact that in flume traction the particles of the load either roll or slide in continuous contact with the fixed bed or else skip from point to point along it, there are two noteworthy exceptions.

When the transported débris includes particles which are small compared to the projections constituting the roughness of the bed, some of the débris finds lodgment among the projections. The roughness of the bed is thus diminished and the process of transportation is modified. The bed comes to be constituted in part of the fixed summits of projections and in part of mobile débris, and the process becomes a blending of flume traction proper and stream traction. When such conditions existed in the experiments it was found that the capacity was essentially that due to stream traction.

---

[1] The formula given by W. J. M. Rankine, in his "Applied mechanics" and elsewhere, for the rolling resistance of a wheel is $R=\frac{Q}{r}\left\{a+b(v-3.28)\right\}$ where R is resistance, Q gross load, r radius of wheel, v velocity in ft./sec., and a and b constants. The experimental values of a and b are such as to give velocity only a moderate influence on the resistance.

The second exception is a phenomenon of rhythm. It is probable that the rate of flume traction is always affected by rhythm, just as is that of stream traction, and the rhythm in load implies a rhythm in efficiency of current. Under certain conditions, of which the most important is small slope, the rhythm is manifested by the making of a local deposit from the load, a patch of débris appearing on the bed of the trough. Such a patch travels slowly downstream, being succeeded after an interval by another. With suitable variation of conditions the patches become more numerous, are regularly spaced, and occupy a greater share of the bed surface. They may even exceed the interspaces in area. When wide apart they are usually shaped in gentle slopes, but as their ranks close they assume the profiles of dunes, with steep frontal faces.

The advance of the débris patches is like that of typical dunes, in that the upstream slopes are eroded while the downstream slopes are aggraded; and in this way their travel is a factor in débris transportation. It does not, however, become the dominant factor, as in the dune phase of stream traction. There is always a large share of the load which passes over the deposits without being arrested and continues its journey across the intervening bare spaces.

In this rhythmic process there is a combination of elements belonging distinctively to flume traction and to stream traction, and it is possible that the process constitutes a transition from one system to the other; but, so far as developed by the experiments, it appears as a phase, a rhythmic phase, of flume traction. The slopes with which it was associated were much flatter than those necessary to carry the same load by the method of stream traction.

TABLE OF OBSERVATIONS.

In the following table the data are arranged primarily by character of bed surface and subordinately by width of channel, discharge, grade of débris, and slope of channel bed. The characters of bed surface are illustrated in Plate III. Load is given in grams per second, width in feet, discharge in cubic feet per second, and slope in percentage.

TABLE 67.—*Observations on flume traction, showing the relation of load to slope and other conditions.*

a. Over a surface of wood, planed and painted.

w	*Q*	*S*	Value of *L* for grade								
			(C)	(E)	(G)	(H)	(I)	(J)	(E_1G_1)	($E_2H_1J_2$)	($E_3H_2I_3J_2$)
1.00	0.363	0.32	9.1	6.1	6.1						
		.50							28		
		.75	58	50	55						
		1 00							95	138	117
		1.28	154	107	126						
		1.50					248		166		
		1.93	294	183	199	243					
		2 00	294	202		268	334		271	397	406
		2 50				453			342		
		2.77		318	360	384					
		3.00	566	366	386	438	636	625	484	783	793
		3.41		444	479	524					
		3.93									1,092
		4.01								1,025	
		4.03	850					1,095	622		
		4.50		660	685	801					
	.734	.32	22.8	20.5	18.1						
		.50							68		
		.75	120	98	110						
		1.00							179	315	335
		1.28	261	212	219						
		1.50							297		
		1.93		372	348	449					
		2.00	561	381		474	660	778	427	909	949
		2.50				899	1,248	570			
		2.77		590	580	721					
		3.00	1,075	640	726	814	1,170	1,595	790	1,557	1,730
		3 41		771	765	976					
		3.93									2,360
		4.01								1,980	
		4 03						2,480	1,278		
		4.50		1,081	1,127	1,468					
1.91	.363	.75	49	41.6	58	30					
		1.28	110	103	117	137					
		1.93	230	193	222	255					
		2.77		324	392	463					
		3.44		439	471	569					
	.736	.75	134	114	147	115					
		1.28	282	222	248	325					
		1.93	432	368	430	501					
		2.77		641	725	799					
		3.44		857	846	1,028					

TABLE 67.—*Observations on flume traction, showing the relation of load to slope and other conditions*—Continued.

b. Over a surface of wood, rough-sawn, unplaned, and unpainted.

w	Q	S	Value of L for grade—					
			(E)	(G)	(H)	(I)	(J)	($E_2H_1I_2$)
1.00	0.363	1.07	...	...	...	...	...	186
		1.88	133	141	178	...	...	...
		2.11	...	...	...	...	...	355
		2.20	...	...	...	304	...	...
		2.88	247	284	342	...	...	...
		3.09	...	...	...	515	...	609
		3.81	358	390	526	...	...	...
		4.15	...	...	...	813	930	881
	.734	1.07	...	...	...	...	...	302
		1.88	269	313	343	...	...	...
		2.11	...	...	...	...	...	646
		2.20	...	...	...	632	...	...
		2.88	461	513	545	...	...	...
		3.09	...	...	...	982	1,558	1,550
		3.81	673	720	772	...	...	...
		4.15	...	...	...	1,605	2,140	1,665

c. Over a surface of rectangular wood blocks, with grain vertical.

w	Q	S	Value of L for grade –					
			(E)	(H)	(I)	(J)	($E_2H_1I_2$)	($E_3H_2I_3J_2$)
1.00	0.734	2.00	315	337	561	750	620	789
		3.00	580	693	962	1,397	1,089	1,360
		4.00	911	1,026	1,497	2,060	1,660	2,020

d. Over a pavement of sand grains, grade (G), set in cement, the débris being also of grade (G).

w	Q	S	L
1.00	0.363	1.00	12.1
		2.00	71
		3.00	175
		4.00	317
	.734	1.00	61.2
		2.00	214
		3.00	413
		4.00	656

e. Over a pavement of pebbles, grades (H) and (I), set in cement.

w	Q	S	Value of L for grade –							
			(E)	(G)	(H)	(I)	(J)	(E_1G_1)	($E_2H_1I_2$)	($E_3H_2I_3J_2$)
1.00	0.734	2.00	225	144	125	...	...	190	228	...
		3.00	425	316	273	196	...	483	636	605
		4.00	630	531	463	401	471	714	992	1,059

ADJUSTMENT OF OBSERVATIONS.

FORMULATION.

In flume traction, as in stream traction, there is a finite slope—competent slope—corresponding to the zero capacity. An inspection of the observational data by plotting served to show that they could advantageously be adjusted by means of the formula based on the theory of competent slope:

$$C=b_1(S-\sigma)^n \quad \text{. . . . . . . (10)}$$

Forty-two observational series were found to give information as to the value of σ. Of these, 26 indicated positive values, three negative, and the remainder values so small as to be of uncertain sign. The mean of the 42 values is +0.29 per cent of slope. Eleven could be compared directly with values adopted in the adjustments of stream traction data, the mean of the eleven values being, for flume traction on a smooth surface +0.14 per cent, and for stream traction +0.28 per cent. This difference is consonant with observed differences in competent slope for the two modes of traction. With the aid of this information, and with use of considerations connected with modifications of the mode of flume traction by rough surfaces, but here omitted, a scheme of values of σ for the observational series of Table 67 was made out. The adjustments were then made, by the graphic methods described in Chapter II; and their results appear in Table 68. The same table records the parameters of the adjusting equations, and also the probable errors.

No adjusted values are given for grade (I) in the first division of the table, for the reason that the data, although apparently based on good observations, are strongly discordant. The observations were retained in the record because an aberrant fact, if established, may prove peculiarly valuable; but in this case the interpretation has not been discovered.

TABLE 68.—*Values of capacity for flume traction, adjusted in relation to slope of channel.*

a. Traction over a surface of wood, planed and painted.

w	Q	S	Value of C for grade—								
			(C)	(E)	(G)	(H)	(I)	(J)	(E_1G_1)	($E_2H_1I_2$)	($E_3H_2I_3J_2$)
1.00	0.363	0.5	28	25.5	25	....	....	....	29	....	....
		1.0	93	74	87	....	....	....	93	138	117
		1.5	186	134	158	....	....	....	170	266	254
		2.0	300	205	234	254	....	....	255	410	408
		2.5	435	283	315	350	....	....	350	568	580
		3.0	590	366	398	451	....	625	450	732	763
		3.5	760	458	486	558	....	860	558	910	955
		4.0	945	553	575	666	....	1,085	666	1,085	1,155
		4.5	....	654	665	780	....	....	....	....	....
Probable error (per cent)....			2.9	3.7	0.8	1.1	....	....	1.3	1.8	1.2
Parameters of adjusting equations. σ...			0.04	0.06	0.25	0.35	....	1.80	0.15	0.25	0.40
n...			1.63	1.40	1.16	1.22	....	.96	1.30	1.29	1.28
b_1...			100	80	122	138	....	520	114	199	223

w	Q	S	Value of C for grade—								
			(C)	(E)	(G)	(H)	(I)	(J)	(E_1G_1)	($E_2H_1I_2$)	($E_3H_2I_3J_2$)
1.00	0.734	0.5	46	54	50	....	....	....	65	....	....
		1.0	177	145	151	....	....	....	179	336	335
		1.5	345	258	268	338	....	....	310	592	635
		2.0	548	382	393	470	....	790	453	870	970
		2.5	790	518	527	645	653	1,220	610	1,160	1,310
		3.0	1,050	665	668	830	910	1,630	770	1,465	1,675
		3.5	1,360	820	815	1,027	1,170	2,030	940	1,790	2,060
		4.0	1,700	985	965	1,235	1,440	2,430	1,108	2,120	2,450
		4.5	....	1,150	1,110	1,450	....	....	....	....	....
Probable error (per cent)....			2.1	1.8	1.7	0.7	....	0.7	1.7	2.7	0.7
Parameters of adjusting equations. σ...			0.03	0.04	0.16	0.22	0.65	1.20	0.10	0.16	0.28
n...			1.60	1.35	1.20	1.29	1.01	.90	1.24	1.20	1.21
b_1...			185	154	187	221	470	965	202	415	500

w	Q	S	Value of C for grade—			
			(C)	(E)	(G)	(H)
1.91	0.363	1.0	77	69	85	75
		1.5	145	130	160	171
		2.0	224	200	241	275
		2.5	....	281	328	381
		3.0	....	370	415	491
		3.5	....	464	507	602
Probable error (per cent.....			......	0.5	3.0	1.5
Parameters of adjusting equations.............. σ...			0.07	0.10	0.30	0.55
n...			1.44	1.42	1.16	1.09
b_1...			86	80	130	182

w	Q	S	Value of C for grade—			
			(C)	(E)	(G)	(H)
1.91	0.734	1.0	197	158	185	204
		1.5	324	281	320	378
		2.0	459	415	460	550
		2.5	....	560	607	730
		3.0	....	720	755	915
		3.5	....	880	910	1,095
Probable error (per cent)....			....	1.4	3.3	2.4
Parameters of adjusting equations............. σ...			0.05	0.08	0.20	0.35
n...			1.16	1.30	1.12	1.06
b_1...			210	176	238	322

TABLE 68.—*Values of capacity for flume traction, adjusted in relation to slope of channel*—Continued.

b. Traction over a surface of wood, rough-sawn.

w	*Q*	*S*	Value of *C* for grade— (E)	(G)	(H)	(I)	(J)	$(E_2H_1I_2)$
1.00	0.363	1.5	97	....	120	....	....	229
		2.0	145	160	195	249	....	341
		2.5	200	220	279	374	....	460
		3.0	259	285	366	500	....	582
		3.5	331	355	460	630	....	710
		4.0	385	427	560	755	895	840
Probable error (per cent)			....	....	....	....	....	4.6
Parameters of adjusting equations.		σ	0.10	0.30	0.40	1.00	....	0.30
		n	1.34	1.12	1.28	1.01	....	1.16
		b_1	62	82	106	248	....	184

w	*Q*	*S*	Value of *C* for grade— (E)	(G)	(H)	(I)	(J)	$(E_2H_1I_2)$
1.00	0.734	1.5	....	....	....	....	....	450
		2.0	290	331	354	538	....	660
		2.5	390	434	462	752	....	885
		3.0	495	540	570	970	1,490	1,115
		3.5	600	648	680	1,100	1,800	1,360
		4.0	712	758	786	1,325	2,100	1,615
Probable error (per cent)			....	....	....	....	....	2.3
Parameters of adjusting equations.		σ	0.08	0.20	0.30	0.65	1.20	0.20
		n	1.25	1.11	1.02	1.06	.76	1.18
		b_1	128	173	207	390	950	325

c. Traction over wood blocks with grain vertical.

w	*Q*	*S*	Value of *C* for grade— (E)	(H)	(I)	(J)	$(E_2H_1I_2)$	$(E_3H_2I_3J_2)$
1.00	0.734	2.0	313	354	540	730	613	780
		2.5	442	507	770	1,090	860	1,075
		3.0	583	673	1,008	1,415	1,110	1,390
		3.5	740	850	1,245	1,740	1,375	1,700
		4.0	900	1,026	1,500	2,040	1,660	2,010
Parameters of adjusting equations.		σ	0.10	0.45	0.75	1.20	0.50	0.60
		n	1.46	1.48	1.05	.81	1.16	1.06
		b_1	123	201	430	880	385	545

d. Traction over pavement of sand grains, grade (G).

w	*S*	Value of *C*. Q=0.363	Q=0.734
1.00	1.0	11	61
	1.5	36	131
	2.0	72	215
	2.5	119	310
	3.0	175	413
	3.5	240	525
	4.0	311	650
Parameters of adjusting equations.	σ	0.50	0.30
	n	1.70	1.72
	b_1	36	101
Probable error (per cent)		1.1	0.1

TABLE 68.—*Values of capacity for flume traction, adjusted in relation to slope of channel*—Continued.

e. Traction over pavement of pebbles, grades (H) and (I).

w	Q	S	Value of C for grade—						
			(E)	(G)	(H)	(I)	(E_1G_1)	($E_2H_1I_2$)	($E_3H_2I_3J_2$)
1.00	0.734	2.0	220	143	122	....	200	250	....
		2.5	313	220	192	....	325	420	....
		3.0	416	310	272	209	460	605	605
		3.5	529	412	363	290	600	800	830
		4.0	650	522	460	393	740	1,015	1,060
Parameters of adjusting equations.		σ...	0.10	0.40	0.55	1.00	1.00	1.00	1.20
		n...	1.50	1.60	1.52	1.65	1.19	1.26	1.28
		b_1...	84	67	68	65	200	250	280

PRECISION.

Probable errors were computed from the residuals of 25 series, the residuals being measured on the plots as percentages. The greatest probable error computed for a series of adjusted values of capacity is ±4.6 per cent, and their average is ±1.3 per cent. The average of the 25 determinations of the probable error of an observation is ±3.8 per cent. The residuals number 139, and their average value, which also is a measure of the precision of the observations, is ±4.3 per cent.

A comparison of these measures with those obtained from the data for stream traction shows that the flume-traction data are decidedly the more harmonious. The average residual is more than twice as great for stream traction as for flume. Part of this difference may be due to the fact that the experiments with flume traction came last and had the benefit of previous experience, but it is to be ascribed chiefly to the fact that in flume traction the slope is constant, while in stream traction it is subject to rhythmic fluctuations.

DISCUSSION.

CAPACITY AND CHANNEL BED.

Data illustrating the influence of the character of the channel bed on the quantity of débris which a stream can transport have been assembled in Table 69. They are taken chiefly from the preceding table, but a few items are from Table 72 and Table 12. A single item, marked as interpolated, is based on a combination of data from Tables 68 and 72. They pertain to all the simple grades and mixed grades with which experiments were made in flume traction; and stream traction is represented, so far as possible, by coordinate data. Comparisons are made for slopes of 2 and 3 per cent and discharges of 0.363 and 0.734 ft.³/sec.

The greatest capacity is in each case associated with the smoothest of the tested channel beds, the surface being that of a plank, planed and painted, with the grain running parallel to the current.

TABLE 69.—*Comparison of capacities for flume traction associated with different characters of channel bed.*

[Width of trough, 1 foot.]

Q	S	Character of channel bed.	Value of C.									
			Simple grades.							Mixtures.		
			(B)	(C)	(E)	(G)	(H)	(I)	(J)	(E_1G_1)	($E_2H_1I_2$)	($E_3H_2I_3J_2$)
0.363	2.0	Planed wood	388	300	205	234	254	364			410	
		Sawn wood			145	160	195	249			341	
		Sand pavement				72						
		Débris	266	245	115	45						
.363	3.0	Planed wood			366	398	451	600			732	
		Sawn wood			259	285	366	509			582	
		Sand pavement				175						
		Débris				120						
.734	2.0	Planed wood		548	382	393	470	711	790	453	870	970
		Sawn wood			290	331	354	538			660	
		Wood block			313		354	540	730		613	780
		Sand pavement				215						
		Gravel pavement			220	143	122			200	250	
		Débris		483	222	145						
.734	3.0	Planed wood			665	668	830	[1,060]	1,630	770	1,465	1,675
		Sawn wood			495	540	570	970	1,490		1,150	
		Wood block			583		673	1,008	1,415		1,110	1,390
		Sand pavement				413						
		Gravel pavement			416	310	272	209		460	605	605

Next in order are two varieties of unplaned wooden surface; the first being that of boards or planks, parallel to the current, retaining the roughness left by the saw; the second a pavement made by sawing planks of Oregon pine into short equal blocks and setting them on edge. Both these surfaces, as well as those described below, are illustrated in Plate III. These two varieties proved to have approximately the same properties in respect to traction, and the capacities associated with them are 23 per cent less than those for planed lumber. The range in ratio is not large for the different experiments, and the value given may be taken as a constant representing the difference in efficiency between new unplaned and planed wooden flumes. The difference tends, however, to diminish with wear, the unplaned lumber becoming smoother and the planed rougher.

The next grade of roughness was given by coarse sand—débris of grade (G)—set in cement, so as to constitute a pavement resembling sandpaper. The only material run over this was débris of the same grade, the special purpose being to compare flume traction with stream traction—the condition of fixed bed with that of mobile bed—when the degree of roughness is the same. The experiments gave the streams 50 per cent greater capacity when sweeping the débris over the fixed bed than when moving it at the same slope by the method of stream traction.

The sand pavement gives capacities half as great, on the average, as the surface of planed lumber, but the contrast is stronger for the smaller discharge and lower slope and less marked for the larger discharge and steeper slope.

The roughest surface used, a pavement of pebbles prepared by setting in cement a mixture of grades (H) and (I), gave still lower capacities. These range from 20 to 62 per cent of the corresponding capacities given by planed lumber. The obstructing influence of the rough bottom is most strongly manifested when the material transported has a coarseness corresponding to the texture of the pavement. For finer material its roughness is mitigated by the lodgment of débris, which has the effect of establishing a pavement of the finer material.

The word "débris" in the table indicates a channel bed composed of loose débris, the débris in transit, and the associated process is that of stream traction. The available data afford comparison only for the four finer grades, (B), (C), (E), and (G), the grades which would be designated sand. Each comparison, with an apparent exception to be considered immediately, shows stream traction to be less efficient than flume traction. When stream traction is compared with flume traction over a smooth surface, the observed ratio of efficiency ranges from 19 to 88 per cent, the smaller ratios being associated with the coarser grades of débris.

The exception occurs when capacity over a bed of débris is compared with capacity over a pavement of pebbles, the two capacities being found to be the same. The cases which afford this comparison are for grades (E) and (G), and these fine materials, by filling the hollows of the pavement, create a condition of bed in which stream traction dominates. The comparison is really between normal stream traction and stream traction modified by the appearance of crests of fixed pebbles in the channel bed. In harmony with this interpretation is the fact that capacities for stream traction and for traction over the gravel pavement, when compared severally with capacity for traction over smooth wood, both show contrasts which increase with coarseness of the load.

The important general facts brought out by the comparisons are (1) that with a given discharge, channel width, and slope, the process of flume traction is able to transport more débris than that of stream traction, and (2) that a stream's capacity for flume traction varies inversely with the roughness of the flume bed.

The first of these principles serves to explain certain phenomena of clogging. When there is fed to a flume a load greater than its stream is able to transport, a portion is deposited. This changes the character of the bed in such a way as to substitute stream traction for flume traction. Stream traction, being less efficient, can carry still less load, and a larger fraction is deposited. If the conditions remain unchanged the bed is built up until its slope becomes that necessary to carry the entire load by stream traction. Unless the trough is deep or short, overflow results.

When clogging is initiated by a temporary overloading, the stream loses power to carry its normal tractional load, and deposition continues unless the load is reduced considerably below the normal. In practical operations the first step toward the abatement of a clog is to stop all feeding of load above the deposit, that the stream may be able to take on load and thereby reduce the deposit.

CAPACITY AND SLOPE.

The rate at which capacity for flume traction is increased by increase of slope is contained implicitly in the values of n and σ assembled in Table 68; for n gives the rate of variation of capacity with $S-\sigma$, and the instantaneous rate of variation of capacity with slope is given by $i_1=\frac{nS}{S-\sigma}$. All the tabulated values of n except two are greater than unity; and in each of the cases where n is less than unity all values of i_1 computed for the range of slopes covered by the experiments are greater than unity. The general fact is thus indicated that, within the practical range of conditions, capacity increases with slope in more than simple ratio. Efficiency also increases as slope increases.

The sensitiveness of capacity to changes in slope varies with changes of condition; and this variation might be illustrated, as in treating of stream traction, by the tabulation and discussion of values of the index of relative variation, i_1. It will suffice, however, in this case to make comparisons by means of the synthetic index, I_1. Table 70 contains values of that index computed between the limits of $S=2.0$ and $S=3.5$. They represent 42 of the 51 series of values given in Table 68, the other nine series not having sufficient range for the computation. The arithmetical mean of the 42 values of I_1 is 1.46, and the range is from 1.08 to 2.08.

TABLE 70.—*Values of I_1 for flume traction, computed between the limits $S=2.0$ and $S=3.5$.*

w	Q	Character of channel bed.	Value of I_1.								
			Simple grades.						Mixtures.		
			(C)	(E)	(G)	(H)	(I)	(J)	(E_1G_1)	($E_2H_1I_2$)	($E_3H_2I_3J_2$)
1.00	0.363	Planed wood	1.66	1.44	1.30	1.41			1.40	1.42	1.52
		Sawn wood		1.43	1.42	1.54	1.66			1.32	
1.00	.734	Planed wood	1.66	1.37	1.30	1.40		1.69	1.30	1.29	1.35
		Sawn wood		1.30	1.20	1.17	1.27			1.08	
		Wood block		1.54		1.56	1.49	1.55		1.44	1.39
		Sand pavement			1.60						
		Gravel pavement		1.56	1.89	1.95			1.96	2.08	
1.91	.363	Planed wood		1.50	1.32	1.40					
1.91	.734	do		1.34	1.22	1.23					

Inspection of these data shows, first, that the values are always greater for $Q=0.363$ than for $Q=0.734$. The experiments deal with no other discharges, but it is probably true in general (as in case of stream traction) that increase of discharge is accompanied by decrease of the sensitiveness of capacity to slope.

If the index varies in a systematic way with fineness of débris, its increase is connected with decrease of fineness, but the finest débris of the table, (C), carries large values of the index. The apparent conflict of evidence has its parallel in the fuller data for stream traction (see p. 108 and fig. 34), and it is possible that the sensitiveness increases in two directions from a minimum value. Its variation might in that case be connected with the law relating capacity to fineness, as brought out in a later section.

The relation of the index to roughness of bed does not follow a simple law. Its values are in general least for the bed of rough lumber and progressively greater for planed lumber, wood blocks, and gravel pavement.

The greater sensitiveness of capacity to slope when the channel bed is a coarse pavement may be connected with the fact that the mode of transportation over such a bed is approximately stream traction; and this suggests that in flume traction the sensitiveness may be less than in stream traction. Direct comparison can not be made with use of the values of I_1 in Table 70, because the slopes used in stream traction experiments have less range; but special computations were made, so far as the data were found to overlap. The results are contained in Table 71 and indicate that the sensitiveness is greater for stream traction than for flume traction over a smooth bed, in case of grades (E) and (G), but less in case of grade (C).

TABLE 71.—*Comparison of values of I_1 for flume traction over a bed of planed wood, with corresponding values for stream traction.*

Width of trough (feet).	Grade of débris.	Discharge (ft.³/sec.).	Limiting values of slope (per cent).	I_1 for flume traction.	I_1 for stream traction.
1.00	(C)	0.363	0.5–2.0	1.71	1.60
		.734	.5–2.0	1.79	1.46
	(E)	.363	.5–2.0	1.50	1.99
		.734	.5–2.0	1.41	1.65
	(G)	.363	2.0–3.0	2.27	2.55
		.734	1.0–2.0	1.38	2.42

Various qualifications and doubts being omitted, the preceding paragraphs may be generalized by saying that the sensitiveness of capacity to slope is somewhat less in flume traction than in stream traction. It varies in both directions from a mean value expressed by the exponent 1.5, being greater as the slope is less, as the discharge is less, as the fineness is less, and as the channel bed is rougher. Efficiency for flume traction increases with slope.

CAPACITY AND DISCHARGE.

Special series of experiments were made to determine the variation of capacity with discharge. In each series the conditions of slope, width, and grade of débris were kept constant and the discharge was varied. The observations are given in Table 72, and the same table contains the adjusted values of capacity, together with the parameters of the adjusting equations. Inspection of logarithmic plots showed the propriety of adjusting by means of the formula used with the data for stream traction,

$$C=b_3(Q-\kappa)^o \text{ . . . . } (64)$$

and the computations were graphic.

TABLE 72.—*Observations and adjusted data illustrating the relation of capacity for flume traction to discharge, for a rectangular flume of planed wood 1 foot wide.*

[*L*, observed load; *C*, adjusted value of capacity; *Q*, discharge.]

Slope		2 per cent.					3 per cent.			
Grade of débris		(B)	(E)	(H)	(I)	($E_2H_1I_2$)	(E)	(H)	(I)	($E_2H_1I_2$)
	Q	*L*	*L*	*L*	*L*	*L*	*L*	*L*	*L*	*L*
Data of observation	0.039	....	....	....	....	....	28.0	25.0	....	....
	.093	54.5	....	....	....	....	79	128	50.6	87
	.182	151	96	136	110	144	169	228	272	325
	.363	388	202	268	385	397	366	446	567	718
	.545	619	322	417	528	617	580	635	922	1,147
	.734	....	446	546	738	907	785	914	1,170	1,550
Parameters of adjusting equations	κ	0.002	0 007	0.040	0.140	0.060	0.004	0.025	0.080	0.040
	o	1.34	1.09	.88	.68	1.05	1.10	.88	.79	.88
	b_3	1,430	630	760	1,000	1,345	1,125	1,175	1,650	2,220
Probable error (per cent)		0.9	0.2	0.4	0.9	0.5	0.3	1.0	0.7	1.4
	Q	*C*	*C*	*C*	*C*	*C*	*C*	*C*	*C*	*C*
Adjusted data	0.039	....	....	....	....	....	28	27	....	....
	.093	58	....	....	....	....	79	108	53	123
	.182	145	95	134	116	146	169	230	270	325
	.363	371	205	279	364	384	364	450	600	730
	.545	640	322	415	548	627	572	670	880	1,130
	.734	....	445	549	711	890	795	870	1,170	1,550

Several values of capacity in Table 72 agree as to conditions with values in Table 68, and these values would be identical if the experiments were homogeneous. A comparison shows that the values given by the experiments comparing capacity and discharge are in general the greater, the average difference being 6 per cent. This is evidently of the nature of systematic error and is probably connected with some change in apparatus or in detail of experimental method which occurred between the making of the two groups of experimental series.

The sensitiveness of capacity to changes of discharge varies with conditions. It is greater as the discharge is less, as the slope is less, and as the channel bed is rougher. It is relatively great for the coarsest and finest of the débris used and less for intermediate grades. Under similar conditions it is less for flume traction than for stream traction. Expressed as an exponent, I_3, its average value for the range of the experiments recorded in Table 72 is 1.26. Values of I_3 were also obtained from data in Table 68 by comparing the capacities for $Q = 0.363$ ft.³/sec. with those for $Q = 0.734$ ft.³/sec.; and the mean of such values is 0.97. These mean values are not necessarily inconsistent, for the synthetic index varies with the range in discharge for which it is computed and is lower as the discharges are higher; but a study of individual values shows that under identical conditions the data of Table 68 give the lower estimates of sensitiveness. The data as a whole indicate that, for the range of conditions realized in the experiments, the average value of the exponent expressing sensitiveness to discharge is 1.2. There can be no question that for the larger discharges used it falls below unity.

As the sensitiveness of the duty of water, and also the efficiency, to discharge is expressed by an exponent which is less by unity than the corresponding exponent for the sensitiveness of capacity to discharge, it follows that duty and efficiency vary little with discharge. In general they gain slightly with increase of discharge, but they lose when the discharge or slope is relatively large. This accords with a result obtained by G. A. Overstrom,[1] who found from experiments with launders that duty rose with increase of depth to a limited extent only.

CAPACITY AND FINENESS.

In Tables 68 and 72 the values of capacity standing in any horizontal line constitute a series illustrating the variations which are related to grades of débris, and if those in the columns for mixtures be excepted they illustrate the relations of capacity to fineness. Table 73 contains a selection of data from those tables, together with a single line taken from Table 69.

TABLE 73.—*Values of capacity for flume traction, illustrating the control of capacity by fineness of débris.*

Character of channel bed.	w	Q	S	Value of C for grade—						
				(B)	(C)	(E)	(G)	(H)	(I)	(J)
Planed wood	1.91	0.734	2.0	....	459	415	460	550	....	....
	1.00	.363	2.0	388	....	202	....	268	383	....
	1.00	.363	3.0	....	590	366	398	451	....	625
	1.00	.734	2.5	....	790	518	527	645	653	1,220
	1.00	.734	3.0	....	1,050	665	668	830	910	1,630
Sawn wood	1.00	.734	3.0	....	....	495	540	570	970	1,490
Wood block	1.00	.734	3.0	....	....	583	....	673	1,008	1,415
Gravel pavement	1.00	.734	....	....	....	416	310	272	200	....
Débris (stream traction)	1.00	.363	2.0	266	245	115	45	....	....	....

As the tables are examined, one of the features arresting attention is that in most of the series the smallest value of capacity does not appear at one end of the line but at some intermediate point. The occurrence of a minimum is in fact characteristic of all tested varieties of flume traction except that in which the bed is a pavement of pebbles. To give the feature graphic expression the data of the last five lines of Table 73 are plotted in figure 69, where the horizontal scale is that of linear fineness, F. The plotted points are far from regular, but the general character of the representative curves is unmistakable, and freehand lines have been drawn. On another sheet, not reproduced, the same data were plotted in relation to mean diameter of particles—the reciprocal of F—with similar result, except that the lower two curves became concave upward.

These curves illustrate the most important difference between the laws of flume traction and those of stream traction. In stream traction capacity increases continuously as fineness increases. In flume traction capacity increases with fineness when the grades of débris compared are relatively fine but increases with coarseness when the grades are relatively coarse. So far as these experiments show, the minimum of capacity corresponds to a coarse sand, but its position on the scale of fineness may be assumed to vary with slope, discharge, and roughness of bed.

The curve for flume traction over a bed paved with gravel shows no minimum but is of the same type as the curve for stream traction. This fact is confirmatory of an inference already drawn (p. 207), that the transportation of fine débris over a fixed bed of coarser débris particles is essentially of the nature of stream traction. It may fairly be inferred that if we were able to extend this curve into the region of débris coarser than the gravel of the bed, a minimum would be developed.

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[1] Quoted by R. H. Richards in Ore dressing.

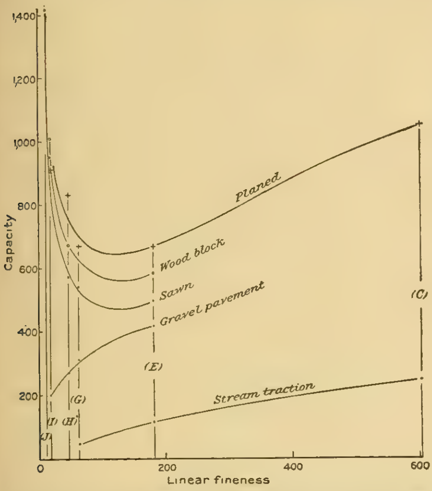

FIGURE 69.—Curves illustrating the relation of capacity for flume traction to fineness of débris. Data from bed of planed wood are recorded by crosses; from wood-block pavement by circles; other data by dots.

If the curves were to be traced toward the right, by means of additional experiments with finer débris, there can be little doubt that they would be found to continue their ascent; but eventually, *as curves of traction*, they would come to an end with the passage of the process of transportation from traction into suspension. In the opposite direction they may be conceived to attain a maximum and then drop suddenly to the base line; for despite the law of increase of capacity with coarseness, there must be a degree of coarseness for which the force of the current is not competent, and when that is reached the ordinate of capacity becomes zero. The position of this limit, which I have in earlier pages called competent fineness, evidently depends on slope and discharge, as determining the force of the current, and on the degree of rounding of the débris.

The double ascent of the curve of flume traction is susceptible of plausible explanation, by means of considerations connected with the process of rolling. The process of rolling involves a question of space. Each rolling pebble occupies an area of the channel bed somewhat larger than its sectional area, even if the pebbles are arranged in the closest possible order. If we conceive the channel bed to be occupied by rolling pebbles of a particular size, separated by spaces which bear a definite ratio to the diameters of the pebbles; and again conceive it to be occupied by rolling pebbles of a larger size, with the same ratio between interspace and diameter; it is evident that the total volumes or masses of pebbles in the two cases will be proportional to the diameters. If the larger pebbles have twice the diameter of the smaller, then a given area of bed will contain twice as much rolling load of the larger pebbles as of the smaller. It is also true, as stated on an earlier page, that the rolling speed is somewhat greater for larger pebbles than for smaller. The tendency of these two factors is the same, to make the load greater for large particles than for small, when the process of transportation is rolling. The analysis is doubtless too simple—the degree of crowding on the bed, for example, may not be the same for different sizes, and the degree of crowding may affect the speed of rolling—but qualifying factors can hardly impair the qualitative inference that the rolling load increases with coarseness.

It is a matter of observation that, under similar conditions determining force of current, the dominant process in flume traction is for coarse débris rolling and for fine débris saltation. When the process is rolling, as just shown, capacity increases with coarseness of débris. When it is saltation, as illustrated by the body of experiments on stream traction, capacity increases with fineness. With the passage from saltation to suspension the effect is even heightened, and it is probable that in a number of the recorded experiments the process was largely that of suspension. Thus the double ascent of the capacity-fineness curve is determined by the distinctive properties of two (or three) modes of propulsion

If the preceding explanation is well founded, the nature of the law connecting capacity with the degree of comminution of the débris in any particular case depends on those conditions which determine the dominant process of conveyance. If the channel bed is smooth, and if slope and discharge are so adjusted as to give a moderate velocity, the progression of sand may be by rolling, and in that case the capacity for different sands will vary inversely with their fineness. But if over the same smooth bed the current runs swiftly, sand will be made to travel by saltation, or by saltation and suspension, and then the capacity for different sands will vary directly with their fineness. The particular velocity with which the function reverses will depend on the quality of the bed, being lower if the bed is somewhat rough, because roughness changes rolling to saltation. The critical velocity will be higher for gravel than for sand, because higher velocity is needed to make coarser débris leap.

The experiments which have been made were not sufficiently varied to afford test for these inferences,. and as there is no present opportunity for continuance of laboratory work the inferences must be regarded as largely hypothetic.

TABLE 74.—*Capacities for flume traction of mixed grades and their component simple grades.*

Character of bed.	Q	Mixed grade.	Capacity for mixture (gm./sec.).	Capacity for single grade (gm./sec.).				
				(E)	(G)	(H)	(I)	(J)
Planed wood	0.363	(E_1G_1)	450	225 366	225 398	....	....	....
Do	.734	(E_1G_1)	770	385 665	385 668	....	....	....
Do	.734	$(E_2H_1I_2)$	1,465	586 665	....	293 830	586 910	....
Do	.734	$(E_3H_2I_3J_2)$	1,675	502 665	....	335 830	502 910	335 1,630
Sawn wood	.363	$(E_2H_1I_2)$	582	233 259	....	116 366	233 500	....
Do	.734	$(E_2H_1I_2)$	1,115	446 495	....	223 570	446 970	....
Wood block	.734	$(E_2H_1I_2)$	1,110	444 583	....	222 673	444 1,008	....
Do	.734	$(E_3H_2I_3J_2)$	1,390	417 583	....	278 673	417 1,008	278 1,415
Gravel pavement	.734	(E_1G_1)	460	230 416	230 310	....	....	....
Do	.734	$(E_2H_1I_2)$	605	242 416	....	121 272	242 209	....
Do	.734	$(E_3H_2I_3J_2)$	605	181 416	....	121 272	181 209	121 ....

MIXTURES.

Three mixtures of simple grades of débris were treated in the laboratory. The components of one, (E_1G_1), were a medium sand and a coarse sand. The others, $(E_2H_1I_2)$ and $(E_3H_2I_3J_2)$, combined medium sand with fine gravel and coarser gravel. All three were tested in relation to slope on the smooth channel bed and on the gravel pavement—one on the rough-sawn bed and two on the bed of wooden blocks. One entered into the experiments on capacity in relation to discharge. The results are contained in Tables 67, 68, and 72. The data from those tables which pertain to a channel width of 1 foot and a channel slope of 3 per cent are assembled in Table 74. The table contains also the capacity quota for each constituent, computed from the capacity for the mixture; and beneath each of these quotas is printed the capacity for the constituent when the entire load is composed of it.

A general fact brought out by this table is that the current can transport more of a mixture than it can of any one of the constituent grades. The table records a single exception, the capacity for the mixture being 1,390 gm./sec., while that for its coarsest constituent grade is 1,415 grams.

Another general fact shown is that the capacity for each component as part of a mixture is less than the capacity for the same component if transported separately. To this also there is a single apparent exception, but as it occurs among the data for traction over a gravel pavement it illustrates a feature of stream traction rather than flume traction.

The two principles may be illustrated together by saying that if a stream is carrying its full load of a grade narrowly limited in range of fineness, and a different grade of débris is added, the total load is thereby increased, but this increase is accompanied by a diminution of the quantity carried of the first-mentioned grade. In contrast with this is the law found for stream traction—that the load of the initially transported grade is increased by the moderate addition of other débris, provided the added débris is relatively fine.

The difference between the two cases is thought to be connected with rolling. In flume traction over a smooth bed the path for rolling particles is roughened by the presence of smaller particles. In stream traction the pathway for larger particles is smoothed by the presence of smaller particles and rolling is promoted.

In stream traction the capacity for a mixture is determined chiefly by the capacity for its finer components, and as mean fineness also depends chiefly on the fineness of the finer components, mean fineness is a serviceable gage of capacity. In flume traction the relation is quite different. Because of the double ascent of the curve of capacity and fineness, it may readily occur that the capacity for a mixture is most nearly related to that for the coarsest component—in fact, that is true of the three mixtures tested in our experiments—and when that is the case there is no parallelism between capacity and mean fineness.

CAPACITY AND FORM RATIO.

The data bearing on the relations of capacity to the depth and width of current, and their ratio, are meager. Most of the experiments were conducted with a single trough width, 1 foot. The only other width used was 1.91 feet, and its use was associated with but four grades of débris and a single character of channel bed—the smoothest.

Depths of current were not in general measured during the passage of loads, because the surfaces of load-bearing currents were usually so rough as to make good determinations impossible. Good measurements were made of unloaded streams, and the results are here tabulated. Attempts to measure depths of loaded streams yielded one result thought worthy of record. With a discharge of 0.734 ft.^{3}/sec., a width of 1 foot, a slope of 4 per cent, and a full load of débris of grade $(E_3H_2I_3J_2)$, the depth was 9 per cent greater than for the corresponding unloaded stream.

Table 76 compares the capacities found for a trough width of 1.91 feet with corresponding capacities for a width of 1 foot. By aid of Table 75 it brings capacities into relation also with depths.

Table 75.—*Depths and form ratios of unloaded streams, in troughs of wood, planed and painted.*

Q	S	$w=1.91$		$w=1.00$	
		d	R	d	R
0.363	1	0.076	0.040	0.120	0.120
	2	.062	.032	.096	.096
	3	.056	.029	.082	.082
.734	1	.119	.062	.194	.194
	2	.098	.051	.154	.154
	3	.086	.045	.136	.136

Table 76.—*Capacities for flume traction in troughs of different widths.*

Q	S	Grade (C).		Grade (E).		Grade (G).		Grade (H).	
		$w=1.91$	$w=1.00$	$w=1.91$	$w=1.00$	$w=1.91$	$w=1.00$	$w=1.91$	$w=1.00$
		Values of C.							
0.363	1.0	77	93	69	74	85	87		
	2.0	224	300	200	205	241	234	275	254
	3.0			370	366	415	398	491	451
.734	1.0	197	177	158	145	185	151		
	2.0	459	548	415	382	460	393	550	470
	3.0			720	665	755	668	915	830
		$\frac{C_{1.91}}{C_{1.00}}$							
.363	1.0	0.83		0.93		0.98			
	2.0	.75		.98		1.03		1.08	
	3.0			1.01		1.04		1.08	
.734	1.0	1.11		1.09		1.22			
	2.0	.89		1.09		1.17		1.17	
	3.0			1.08		1.13		1.10	

Simple combinations of the quantities, into which it is not necessary to enter, show (1) that with constant depth, capacity increases with width and more rapidly than width, and (2) that with constant width, capacity increases with depth and more rapidly than depth. The rate of increase with depth, if expressed as an exponent, may be as low as 1.2 or as high as 2.0. From these premises, a line of reasoning parallel to that of Chapter IV shows that for flume traction, as for stream traction, the function $C=f(R)$ increases to a maximum and then decreases. The value of R corresponding to maximum capacity—the optimum form ratio—can not be determined from observations involving but two channel widths, but its limits can in some cases be indicated. For example, when the capacities conditioned by the same slope and discharge are approximately the same for the two trough widths, it may be inferred that the optimum falls between the values of R associated with the two capacities. Thus for grades (E), coarse sand, with a slope of 2 per cent, the capacities are about the same for the two widths, while the form ratios are 0.032 and 0.096, or one-thirtieth and one-tenth; and it is inferred that the optimum form ratio falls between those fractions.

From inferences of this sort, used in combination with the general principles of flume traction, a number of tentative conclusions have been drawn. They are of so hypothetic a character that the reasoning connected with them is not thought worthy of record, but the conclusions themselves may perhaps be of some service, until replaced by others of more secure foundation. They are: The ratio of depth to width giving a current the highest efficiency for flume traction (1) is greater for gentle slopes than for steep, (2) is greater for small discharge than for large, (3) is greater for fine débris than for coarse, (4) is greater for rough than for smooth channel beds, and (5) is in general less than for stream traction. The first and second propositions apply also to stream traction. The third is the reverse of the relation determined for stream traction, and its applicability may be limited to conditions under which rolling is the dominant mode of transit. By aid of the fifth and fourth Table 31 may be roughly applied to practical problems of flume traction.

TROUGH OF SEMICIRCULAR CROSS SECTION.

A few experiments were made with a trough of galvanized sheet iron, 1 foot wide, having a semicircular section. It was given a slope of 1 per cent, and in it were tested four grades of débris. The observational data appear in Table 77. The object of the experiments was to determine whether a channel with curved perimeter is more efficient or less efficient than one with rectangular section; the capacities obtained are compared, in the table, with those determined for a flat-bottomed trough of the same width. As the discharge used did not fill the semicylindric trough, the width of water surface was less than 1 foot. The width of channel bed occupied by the load ranged from one-fifth to one-half of the width of water surface. The medial depth of water was greater than in the rectangular channel, and the mean velocity was higher. The higher velocity is a factor favorable to the development of capacity; the narrower field of traction is an unfavorable factor. The resultant of the two was unfavorable, the capacities for the semicylindric trough being only half as great as for the rectangular. The result is qualified by the fact that the troughs compared were not of the same material, but the disparity of capacities is too great to be ascribed to that factor.

TABLE 77.—*Data on flume traction in a semicylindric iron trough of 0.5 foot radius; with comparative data for a rectangular wooden trough 1 foot wide.*

Slope (per cent).	Discharge (ft.³/sec.).	Grade of débris.	Capacity (gm./sec.).	
			In semicylindric trough.	In rectangular trough.
1.00	0.363	(C)	43	93
		(E)	33	74
		(F)	37	....
	.734	(E)	64	145
		(F)	66	....
		(G)	74	151
Depth of unloaded stream (foot)	$Q=0.363$		0.181	0.120
	$Q=0.734$		.257	.194
Width of water surface, unloaded stream (foot)	$Q=0.363$		.770	1.00
	$Q=0.734$		.874	1.00
Width of bed occupied by load (foot)			.17 to .37	1.00
Mean velocity of unloaded stream (ft./sec.)	$Q=0.363$		3.85	3.02
	$Q=0.734$		4.60	3.78

The fact that the doubling of the discharge did not double the observed load indicates that the duty of water diminishes as discharge increases, but the data are too few to give confidence to the inference. The three capacities with a discharge of 0.363 ft.^{3}/sec. indicate a minimum in the curve of $C=f(F)$, thus supporting the generalizations already made from the results with rectangular troughs.

The low efficiency here found for an open channel having a circular arc for its perimeter suggests that the cylindric form commonly given to closed conduits for the hydraulic conveyance of débris may not be the most efficient.

A second suggestion is connected with the fact that the semicylindric trough, while it narrows the field of traction, at the same time gives a high velocity to the water. It thus concentrates the available force and energy on the narrow field. Though the result is not favorable to capacity, it may be favorable to competence. When but a small load is to be transported, the practical problem may be one of competent velocity; and such a trough appears well adapted to the production of competent velocity with economy of discharge and slope.

SUMMARY.

In the transportation of débris in flumes much of the movement is usually by rolling and sliding. This is especially true if the current is gentle or the débris coarse. With a very swift current or with fine débris the particles travel by a series of leaps, and with the finest débris the load is suspended. When the conditions are such that the principal movement is by rolling and sliding, the capacity of the current increases with the coarseness of the débris transported, this law holding good up to the limit of coarseness at which the current is barely competent to start the particles. When the conditions are such that the principal movement is by saltation, the capacity of the current increases with the fineness of the débris, the law holding good up to and probably beyond the critical fineness at which the current is competent to carry the débris in suspension.

Under all conditions the capacity is increased by steepening the slope, and the increase of capacity is more rapid than the increase of slope. The capacity may vary with a power of the slope as low as the 1.2 power, or with one higher than the second. A general average for the experimental determinations is the 1.5 power.

Under all conditions the capacity is increased by enlarging the discharge. It may be increased in the same ratio, in a higher ratio, or in a somewhat lower ratio.

The highest capacity is associated with the smoothest channel bed. Progressive increase of roughness reduces capacity progressively until the texture of the bed becomes coarser than the débris of the load. The mode of transportation then passes from flume traction to stream traction. Under like conditions of slope, discharge, and character of débris, flume traction gives higher capacities than stream traction.

Rectangular or box flumes have higher capacity than semicylindric flumes of similar width. Up to a limit, which varies with conditions, the capacity is enlarged by increasing the width of channel at the expense of depth of current. The ratio of depth to width which gives highest efficiency has not been well covered by the experiments, but it is believed to be rarely greater than 1:10 and often as small as 1:30. For large operations the determination of width will usually represent a compromise between efficiency and the cost of construction and maintenance.

As most of the experiments were made with sorted débris, each grade being narrowly limited as to range in the size of its particles, and as most practical work is with aggregations having great range in size, the loads and capacities here reported need qualification. By experiments with mixtures of the laboratory grades it was found that the load carried of a mixture is greater than the load of any one of its important components taken separately. It is in general true that the capacities for complex natural grades of débris are greater than the tabulated capacities for the laboratory grades they most nearly resemble.

COMPETENCE.

The experiments in flume traction were practically limited in their range by phenomena of competence, and these limitations were of use in determining values of σ, κ, and ϕ, but no effort was made to observe competence directly and precisely. There are, however, a few observations by others, which may properly be assembled here, although it is not practicable to use them as checks on our work. Our indefinite data pertain to slope and discharge, while the observations of others pertain to velocity.

The experiments of Dubuat[1] (1783) have been assumed, both by him and by others, to pertain to stream traction, but his account of apparatus and methods makes it probable that what he really investigated was chiefly competence for flume traction. He used a trough of plank, with the grain lengthwise, and measured the velocity of the current by observing the speed of balls slightly heavier than water as they were swept along the bottom. In a current of a particular velocity he placed successively various kinds of débris and noted their behavior, then changed the velocity and repeated. His results are as follows:

	Competent bed velocity (ft./sec.).	
Potter's clay	Between 0.27	and 0.35
Coarse angular sand	0.7	1.1
River gravel:		
Size of anise seed	0.35	0.53
Size of peas	0.62	0.7
Size of common beans	1.1	1.55
Rounded pebbles, 1 inch in diameter	2.1	3.2
Angular flints, size of hen's eggs	3.2	4.0

J. W. Bazalgette, in discussing the flushing of sewers and therefore presumably considering flume traction rather than stream traction, quotes the following results of experiments by Robison:[2]

	Competent bed velocity (ft./sec.).
Fine sand	0.5
Sand coarse as linseed	.67
Fine gravel	1.0
Round pebbles, 1 inch in diameter	2.0
Angular stones, size of eggs	3.0

In 1857 T. E. Blackwell[3] conducted elaborate experiments to determine the velocities necessary to move various materials in sewers. His channel was of rough-sawn plank, 60 feet long and 4 feet wide, with level bottom. Velocities were measured by a tachometer, but the relation of the velocity measurements to the bed is not stated. The tests were applied to natural débris of various kinds and also to types of artificial objects likely to enter sewers. The objects were treated singly and in aggregates, with the general result that an aggregation requires higher velocity to move it than does a single object. It is evident that the experiments on single objects pertain to flume traction and some of those on aggregations to stream traction. From his tabulated results the subjoined data are selected as representing or illustrating the velocities competent for natural débris, the column of mean diameter being added by me. He infers from the experiments that (1) for objects of the same character competent velocity increases with the mass; (2) for objects of the same size and form it increases with the specific gravity; (3) for objects of different form it is greater in proportion as they depart from the form of a sphere; and (4) for objects in motion the rate of travel increases with the velocity of the current.

TABLE 78.—*Observations by Blackwell on velocity competent for traction.*

Material.	Volume.	Mean diameter.	Competent velocity.
Single objects (illustrating flume traction):	*Cubic inches.*	*Feet.*	*Ft./sec.*
Brickbat (roughly cuboid)	18.5	0.27	2.75–3.00
Do	12.98	.24	2.25–2.50
Do	13.6	.25	2.00–2.25
Do	7.33	.20	2.00–2.25
Do	4.76	.17	2.25–2.50
Do	2.59	.14	1.75–2.00
Flint (subangular)	10.37	.22	3.00–3.25
Do	6.05	.19	2.00–2.25
Do	4.11	.16	2.25–2.50
Do	1.95	.13	2.50–2.75
Bowlder (well rounded)		.20	1.50–1.75
Do		.16	2.25–2.50
Bowlder (fairly rounded)		.13	2.50–2.75
Aggregations (illustrating stream traction):			
Gravel		.042	2.25–2.50
Do		.021	1.25–1.50
Sand			0 –1.00

WORK OF OVERSTROM AND BLUE.

Certain experimental work on the capacity of currents for flume traction has for its specific purpose the determination of dimensions for launders, the flumes in which pulverized ore is conveyed. R. H. Richards's "Ore dressing"[4] contains an abstract of results obtained by G. A. Overstrom, accompanied by the statement that the experimental data are extensive but as yet unpublished. The troughs employed were flat-bottomed and probably of wood. For each slope, width of flume, and grade of transported material he found (1) that the duty of water varies with the discharge and that some particular discharge is associated with a maximum duty, so as to be the most economical; (2) that the most economical discharge is sensibly proportional to the width, so that for each slope and grade of material there is a particular discharge per unit of width giving a maximum duty; and (3) that the most economical discharge is greater for low slopes than for high.

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[1] Dubuat-Nançay, L. G., Principes d'hydraulique, vol. 1, p. 100; vol 2, pp. 57, 79, 95, Paris, 1786.

[2] Inst. Civil Eng. Proc., vol. 24, pp. 289–290, 1865.

[3] Accounts and papers [London], Sess. 2, 1857; Metropolitan drainage, vol. 36, Appendix IV, pp. 167–170, Pls. 1–5.

[4] Vol. 3, pp. 1592–1594, 1909.

The first of these results is in fair accord with our own. Five of the nine values of the exponent o in Table 72 are less than unity. For the corresponding series the values of i_3 range both below and above unity and the corresponding values of the variable exponent for duty in relation to discharge, i_3-1, range below and above zero. The value zero evidently corresponds to a maximum value of duty. His third result is in strict accordance with ours; his second can not be compared without fuller details.

A diagram exhibiting his determinations for the traction of crushed quartz sized by 40-mesh and 150-mesh sieves shows for different discharges per unit width the variation of duty with slope. For the larger discharges duty varies as the first power of slope; for the smallest discharge with the second power. This corresponds to a variation of capacity with the second to third power of slope. Our most available data for comparison are those of grade (C), the capacity for which varies with the 1.66 power of slope (Table 70). As grade (C) was separated by 30-mesh and 40-mesh sieves, it is considerably coarser than the crushed quartz, and, being stream worn, it is less angular. The marked difference in the observed laws of variation is evidently susceptible of more than one interpretation, but it is thought to be connected with difference in fineness, as more fully stated on a following page.

F. K. Blue[1] made a series of experiments in which the trough was of sheet iron, 50 feet long, 5 inches deep, and 4 inches wide, the bottom being semicylindric with 2-inch radius. It was so mounted that it could be set to any slope up to 12 per cent. Two materials were used as load, the first a beach sand of 60-mesh average fineness, the other a sharp quartz sand of about 80-mesh fineness, containing about 10 per cent of slime from a stamp mill. With each material the discharge and load were varied; and for each combination of discharge and load the slope was adjusted to competence, and mean velocity was determined by means of a measurement of depth. Discharge and load were not measured directly but in certain combinations. Instead of discharge, the total volume of water and load was measured. This quantity was used chiefly in the computation of mean velocity, for which purpose it is better fitted than is discharge alone. Load was measured as a volume, the volume of the transported material as collected in a settling tank, and is reported only through a ratio, q, which is the quotient of the volume of load by the volume of discharge plus load. This is essentially a duty but differs materially from duty $\left(U=\frac{C}{Q}\right)$ as defined in the present report. Representing by W the weight in grams of a cubic foot of débris, including voids, and by v the percentage of voids, it follows from the definitions that

$$q=\frac{U}{W+U(1-v)}, \text{ and } U=\frac{qW}{1-q(1-v)}$$

From the discussion of his data Blue finds (1) that q varies as the square of the slope and (2) that it varies as the sixth power of the mean velocity. He does not specifically consider the relation of q to discharge, but examination of his tabulated data shows that q is but slightly sensitive to variations of discharge plus load.

As Blue's coarsest material, the beach sand, has approximately the fineness of our grade (A), while the finest we treated in flume traction is of grade (C), the most definite comparison of results can not be made, but there is nevertheless interest in such comparison as is possible. Computing values of U from his data for beach sand, and plotting them in relation to slope, I obtained $U \propto S^{2.02}$ This gives for capacity and slope, $C \propto S^{3.02}$; and the exponent 3.02 may be compared with values of I_1 in Table 70, for the smoothest kind of trough bed. The exponent for grade (C) is 1.66, and the exponent has a minimum value of 1.30 for grade (G). In accordance with the generalization (p. 208) that the sensitiveness of capacity to slope increases from a minimum toward both coarse grades and fine, we should expect for grade (A) an index of sensitiveness materially greater than 1.66. The data furnished by Blue thus tend to support the generalization, and additional support is given by Overstrom's data, above cited. Such an inference is qualified as to Blue's data by the possibility that the exponent is affected in material degree by the form of the cross section of the trough.

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[1] Eng. and Min. Jour., vol. 84, pp. 536–539, 1907.

Blue's data on velocity are of such character as to warrant a fuller discussion than he gives. His comparison with duty (q) is made without regard to the accessory conditions of discharge, depth, and slope, but we have seen that in stream traction these conditions materially affect the control of capacity and duty by mean velocity. It is not practicable so to arrange his data as to obtain results for the condition that discharge, depth, or slope is constant, but moderate approximations to such conditions may be obtained by grouping. I have divided his observations on the traction of beach sand into three groups—first, with reference to discharge (+load); second, with reference to depth; and, third, with reference to slope—and for each group have computed *n* on the assumption that capacity varies with the *n*th power of mean velocity. The resulting values are given in Table 79, and with them are placed the average of the corresponding exponents for stream traction, derived under the several conditions of constant discharge, constant depth, and constant slope (Table 53).

It appears (1) that in flume traction capacity is much more sensitive to variation of mean velocity than in stream traction; and (2) that in flume traction, as in stream traction, the order of sensitiveness as related to conditions is highest for constant discharge, intermediate for constant depth, and lowest for constant slope. In flume traction the sensitiveness appears to vary directly with discharge and depth and inversely with slope, while in stream traction it was found to vary inversely with discharge and slope, the variation with depth being indeterminate.

TABLE 79.—*Value of n in $C \propto V_m^n$, based on Blue's experiments on flume traction of beach sand.*

	Value of n under condition that small range is given to—		
	Q	d	S
The values of Q, d, or S being relatively—			
Small	5.7	5.7	3.6
Intermediate	6.2	5.0	5.0
Large	7.5	7.0	3.3
Mean	6.5	5.9	4.0
Comparative values of I_V from Table 53	3.98	3.68	3.21

CHAPTER XIII.—APPLICATION TO NATURAL STREAMS.

INTRODUCTION.

The flow of a river is a complex phenomenon. The transportation of débris by it involves intricate reactions. The quantity of débris transported depends on a variety of conditions, and these conditions interact one on another. Direct observation of what takes place at the base of the current is so difficult that the body of information thus obtained is small. In the work of the Berkeley laboratory the attempt was made to study the influence of each condition separately, and to that end all the conditions were subjected to control. This involved the substitution of the artificial for the natural; and while the principles discovered are such as must enter into the work of natural streams, their combinations there are different from the combinations of the laboratory. It is the province of the present chapter to consider the differences between the laboratory streams and natural streams, and in view of those differences the applicability of the laboratory results to problems connected with natural streams.

FEATURES DISTINGUISHING NATURAL STREAMS.

KINDS OF STREAMS.

Classification necessarily involves a purpose, or point of view, and there are in general as many scientific, or natural, or otherwise commendable classifications as there are functions to be subserved. The classification of streams here given has no other purpose than to afford a terminology convenient to the subject of débris transportation.

When the débris supplied to a stream is less than its capacity the stream erodes its bed, and if the condition is other than temporary the current reaches bedrock. The dragging of the load over the rock wears, or abrades, or corrades it. When the supply of débris equals or exceeds the capacity of the stream bedrock is not reached by the current, but the stream bed is constituted wholly of débris. Some streams with beds of débris have channel walls of rock, which rigidly limit their width and otherwise restrain their development. Most streams with beds of débris have one or both banks of previously deposited débris or alluvium, and these streams are able to shift their courses by eroding their banks. The several conditions thus outlined will be indicated by speaking of streams as *corrading*, or *rock-walled*, or *alluvial*. In strictness, these terms apply to local phases of stream habit rather than to entire streams. Most rivers and many creeks are corrading streams in parts of their courses and alluvial in other parts.

Whenever and wherever a stream's capacity is overtaxed by the supply of débris brought from points above a deposit is made, building up the bed. If the supply is less than the capacity, and if the bed is of débris, erosion results. Through these processes streams adjust their profiles to their supplies of débris. The process of adjustment is called gradation; a stream which builds up its bed is said to aggrade and one which reduces it is said to degrade.

An alluvial stream is usually an aggrading stream also; and when that is the case it is bordered by an alluvial plain, called a flood plain, over which the water spreads in time of flood.

If the general slope descended by an alluvial stream is relatively steep, its course is relatively direct and the bends to right and left are of small angular amount. If the general slope is relatively gentle, the stream winds in an intricate manner; part of its course may be in directions opposite to the general course, and some of its curves may swing through 180° or more. This distinction is embodied in the terms *direct alluvial* stream and *meandering* stream. The particular magnitude of general slope by which the two classes are separated is greater for small streams than for large. Because fineness is one of the conditions determining the general slope of an alluvial plain, and because the gentler slopes go with the finer alluvium, it is true in the main that meandering streams are associated with fine alluvium.

FEATURES CONNECTED WITH CURVATURE OF CHANNEL.

As nearly all the laboratory experiments were performed with straight channels, and as all natural channels are more or less curved, the features resulting from curvature constitute differences of which account must be taken in applying laboratory results. Some of these differences have been mentioned in connection with the short series of experiments with curved and bent channels, but a fuller account is desirable.

In a straight channel the current is swifter near the middle than near the sides and is swifter above mid-depth than below. On arriving at a bend the whole stream resists change of course, but the resistance is more effective for the swifter parts of the stream than for the slower. The upper central part is deflected least and projects itself against the outer bank. In so doing it displaces the slow-flowing water previously near that bank, and that water descends obliquely. The descending water displaces in turn the slow-flowing lower water, which is crowded toward the inner bank, while the water previously near that bank moves toward the middle as an upper layer. One general result is a twisting movement, the upper parts of the current tending toward the outer bank and the lower toward the inner.[1] Another result is that the swiftest current is no longer medial, but is near the outer or concave bank. Connected with these two is a gradation of velocities across the bottom, the greater velocities being near the outer bank. The bed velocities near the outer bank are not only much greater than those near the inner bank, but they are greater than any bed velocities in a relatively straight part of the stream. They have therefore greater capacity for traction, and by increasing the tractional load they erode until an equilibrium is attained. On the other hand, the currents which, crossing the bed obliquely, approach the inner bank are slackening currents, and they deposit what they can no longer carry.

It results that the cross section on a curve is asymmetric, the greatest depth being near the outer bank. As the winding stream changes the direction of its curvature from one side to the other, the twisting system of current filaments is reversed, and with it the system of depths, but the process of change includes a phase with more equable distribution of velocities, and this phase produces a shoal separating the two deeps. The shoal does not cross the channel in a direction at right angles to its sides but is somewhat oblique in position, tending to run from the inner bank of one curve to the inner bank of the other. In meandering streams it is usually narrow and is appropriately called a bar. In direct alluvial streams, where bends are apt to be separated by long, nearly straight reaches, it is usually broad and may for a distance occupy the entire width of the channel. In navigated rivers the locality of the bar is usually called a crossing, being the place where the thalweg, the line of strongest current, and the route of travel cross from side to side; and the name is often applied also to the bar itself.

The twisting current attacks the outer bank, being swifter at contact with that bank than in any other part of the wetted perimeter. If the bank consists of alluvium there is erosion, the amount being determined in part by resistances arising from roots, or adhesion of alluvial particles, or incipient cementation; and the eroded material, so far as it joins the bed load, helps to satisfy the bed current and limit downward erosion. In alluvial streams the erosion from concave banks offsets the deposition under convex banks, so that the channel may gradually shift its position without change of sectional area.

The sectional area may be either greater or less at a curve than on a reach, but the differences are normally[1] of small amount. Therefore the mean velocity does not vary greatly. The current in a curved channel, as compared to that in a straight channel, is characterized by diversity. Its bed velocities are both higher and lower, and the same is true of velocities along the banks. This diversity is favorable to traction, because capacity for traction varies with a high power of velocity; but the advantage to traction is partly offset by the fact that increase of velocity affects a smaller portion of the wetted perimeter than is affected by reduction of velocity. There is also diversity in the directions followed by elements of current, and this diversity includes not only the twisting movement but various minor eddies and swirls. Diversified movements, by including upward movements, promote suspension, and in conjunction with diversified velocities they modify the partition of the load between traction and suspension. On the whole, suspension claims more in a diversified current, but it is also true that the line of separation between suspension and traction shifts to and fro in such a current. Much débris which is suspended in the swift water under the concave bank joins the bed load in passing the shoal between deeps, and the suspended load is still more restricted in passing the shoal of the convex bank. Deposition on the latter shoal includes both tractional and suspensional materials.

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[1] The system of movements here described has been observed by many students of rivers. They were demonstrated by the aid of a model channel by J. Thomson, in connection with an explanation which differs somewhat from that of the present text. See Roy. Soc. London Proc., pp. 5–8, 1876, and 356–357, 1877; also Inst. Mech. Eng. Proc., pp. 456–460, 1879.

[1] That is to say, they are of small amount when the system of depths is adjusted to the discharge, as explained on a later page.

FEATURES CONNECTED WITH DIVERSITY OF DISCHARGE.

All streams vary in volume from season to season and from year to year. In a stream fed by springs the changes may be slight. At the opposite extreme are creeks and even rivers which exist only during storms. In most large streams the discharge at flood stage is many times greater than at low stage. Usually flood stages continue only for brief periods and in the aggregate occupy but a small fraction of the year.

It is broadly true that streams give shape to their own channels, and among alluvial streams there are few exceptions. It is broadly true also that the shapes of channels, including cross sections and plans, are the same for large streams as for small. But the large stream requires and develops a larger channel—broader, deeper, and winding in larger curves. Through variation of discharge the same stream is alternately large and small, so that its needs are different at different stages. At each stage it tends to fit its channel to the needs of the particular discharge. The formative forces residing in the current are so much stronger with large discharge than with small that the greater features of channel are adjusted to large discharge, and this despite the fact that floods are of brief duration. The feebler forces of smaller discharges modify the flood-made forms but do not succeed in completing their work of adjustment before it is interrupted by another flood. The deeps of high stage are pools at low stage and have currents too feeble for traction. As the reduced stream passes from pool to pool it crosses the shoal formed at high stage with quickened current. The velocities are still diversified, but the greater and smaller velocities have exchanged places. The slope of water surface is more diversified than at high stage, being lower at the pools and higher between them. Traction is restricted to the shoals, and the loads are small. The load at each shoal is obtained from the shoal itself and is deposited in the next pool, and in this way shallow channels are developed from pool to pool.

In contrasting the features of high and low stages, it has been convenient to use the terms as if high stage and low stage were specific and definite phases of stream activity, thereby ignoring the actual diversity in fluctuations of discharge. Floods are of all magnitudes, and each flood presents not only a maximum discharge but a continuous series of changing discharges. At each instant the stream contains a system of currents of which the details depend not only on the discharge but on the shapes of channel created by the work of previous discharges. So long as the discharge continues, its currents are eroding and depositing in such way as to remodel the channel for its own needs, and so long as the work of remodeling continues the loads and capacities at different cross sections are different.

With the changes in the values and distribution of velocities go changes in those values of competent fineness which on one side limit traction and on the other separate traction from suspension. With maximum discharge all the coarser grades of débris within the domain of the stream are in transit along the path of highest activity, and that path includes the deeps and the intervening shoals. With lessening discharge the coarsest material stops, but it stops chiefly in the deeps, because the change in bed velocity is there greatest. At the same time the coarsest of the suspended load escapes from the body of the stream and joins the bed load. By this double change the mean fineness of the tractional load is increased, and so also is the mean fineness of the suspended load. With continued reduction of discharge the tractional load in the deeps becomes gradually finer and at last ceases to move, while the graduated deposit caused by its arrest receives a final contribution from the suspended load. The tractional load on the shoals changes less in mean fineness and may cease to change altogether when the supply from the deep is cut off. It is then derived wholly from the subjacent bed and is greatly reduced in quantity. Soon the derivation becomes selective, the finer part being carried on while the coarser remains, with the result that the shallow channels on the bars come to be paved with particles which the enfeebled currents can not move.

If the section of the alluvium underlying a shoal be afterwards exposed, it is seen to be in the main heterogeneous but veneered at the top by a layer of its coarser particles. The typical section of a deposit in a deep shows the coarsest débris below and the finest at top, with a gradual change.

With the return of large discharge the modeling work of smaller discharges is rapidly obliterated, and the débris deposited in the pools rejoins the tractional and suspended loads.

SECTIONS OF CHANNEL.

Rock-walled channels result from the aggradation of corraded channels. Often they are recurrent temporary conditions of corraded channels. Their widths have been developed in connection with the work of corrasion and are less than the widths of alluvial streams. In the fact that their sides are immobile they resemble the laboratory channels, and their types of cross section are illustrated by the experiments with crooked channels. The channels of all alluvial streams are strongly asymmetric at the bends, and in the meandering streams the bends constitute the greater part of the course. Departure from symmetry is less pronounced in the reaches of direct alluvial streams, but even there a close approximation to symmetry is exceptional.

Alluvial streams tend to broaden their channels by eroding one or both banks. The influence of vegetation opposes this tendency. Often the erosion of the bank exposes roots, and some trees extend rootlets into the water. At low stages the bared parts of the flood channel are occupied by young plants. In these ways vegetation creates obstacles which retard the current at its contact with the bank and thus oppose erosion. If the current is strong erosion is merely retarded, not prevented; if the current is weak deposition may be induced. As a meandering stream encroaches on its concave bank, the convex bank encroaches on the stream, and channel width is maintained. A large stream is less affected than a small stream by the opposition of vegetation and maintains a channel of relatively small form ratio.

Some streams aggrade so rapidly that vegetation does not secure a foothold. By erosion of its banks such a stream broadens its channel and reduces its depth until the slackened current clogs itself by deposition of its load. The built-up bed becomes higher than the adjacent alluvial plain, and the stream takes a new course. Before the assumption of the new course the banks are overtopped by shallow distributaries which deposit their loads on the banks, thus building them up, until the stream is made to flow on a sort of elevated conduit; and when the main body of water at last leaves this pathway, it is apt to start its new course with a steepened slope and scour for itself a relatively narrow channel.

The building up of the bank by deposition from overflow is more pronounced in the presence of vegetation. The ridge thus created is called a *natural levee.* Its crest separates the channel from the flood plain and delimits at flood stage two provinces in which the conditions affecting transportation are strongly contrasted. In both provinces the general slope of the water surface is the same, but the broad sheet covering the plain has so little depth that its currents are sluggish. Between the banks are the normal channel depths and currents, and transportation is active, alike by traction and suspension. Beyond them transportation is effected almost wholly by suspension, and the coarser particles of the suspended load are deposited. As the flood subsides the lateral sheets of water are returned to the main channel by a draining process which involves the making and maintenance of small channels within the plain.

When the channel of a river is fully adjusted to the discharge the same load is transported through each section. All sections are then equally adapted to transportation, though in different ways. The most symmetric has a wide space at the bottom devoted to traction.

The least symmetric has a relatively narrow tractional space, but traction is there relatively active. The partition of the load between traction and suspension is not the same for the two sections, the tractional load having the greater range in the symmetric section and the suspended load in the asymmetric.

There is reason to believe that the sectional area is about the same in different parts of an adjusted channel. At low stages, when form is least adjusted to discharge, the sectional area is much larger for the asymmetric sections. At higher stages the contrast is less, and the greater area may be associated with either type of section. It is also true, if attention be restricted to the channel proper and the expansions over flood plains be excluded, that the variations in width from point to point of an adjusted channel are not of large amount. If it were strictly true that both sectional areas and widths are equal in different parts of an adjusted channel, it would follow (1) that mean depths are equal, and (2) that form ratios are equal, provided form ratio be defined as the ratio of mean depth to width. Such a generalization, while crude and doubtless subject to important qualification, nevertheless warrants the selection of mean depth rather than maximum depth as the quantity to be used in applying the conception of form ratio to rivers.

Assuming the generalization as an approximation to the actual fact and connecting with it the fact that all sections of an adjusted river are equally efficient for transportation, we are able to make a general application of the laboratory results on optimum form ratio to rivers. The ratio of mean depth to width in alluvial rivers, as a class, is very much smaller than in the laboratory examples by means of which the optimum ratio was discussed in Chapter IV. It is so much smaller that the range of form ratio for alluvial rivers overlaps but slightly the range observed in the laboratory. This disparity indicates, though without demonstrating, that the form ratios of the rivers are less than the optimum, and that their tractional capacities would be greater if they were narrower and deeper. As the optimum ratio is the one which enables a stream to transport its load with the least expenditure of head, it is probable that the slopes of most alluvial rivers can be lessened by artificially reducing their widths.

THE SUSPENDED LOAD.

In speaking above of the transfer of load from traction to suspension no consideration was given to capacity for suspension. Certain students of rivers, comparing discharges or velocities with the percentage of suspended material and finding a rough correspondence, have inferred that suspended load is a function of velocity; others, giving attention to conspicuous examples of noncorrespondence, have inferred that the suspended load depends only on the supply of suitable material. There is a measure of truth in both views, and their divergence is largely to be explained by considerations connected with competence.

The subject is illustrated by observations on the suspended load of Yuba River. Its water was sampled during flood stages, in 1879[1] at Marysville, a load of 0.35 per cent, by weight, being found when the discharge was estimated at 26,000 ft.^{3}/sec., and a load of 0.42 per cent when the discharge was 18,000 ft.^{3}/sec. In 1906, at a time when the discharge was estimated at 33,000 ft.^{3}/sec., samples were taken at the same place and the load was found to be only 0.065 per cent. At the time of the earlier samplings hydraulic mining was in full operation in the basin of the Yuba, and the suspended load consisted chiefly of clay components of the auriferous gravels, artificially fed to the stream. In 1906 there was little hydraulic mining and the suspended load consisted of material washed from the surface of the land by rain.

At low stages in 1906 the water at Marysville was clear, but in 1879 a sampling when the discharge was 510 ft.^{3}/sec. gave a load of 0.86 per cent. The fact that the river's load in 1879 constituted a higher percentage at low stage than during flood is explained by the consideration that the turbid tributaries from the mines were less diluted by other tributaries at low stage than at high.

If we assume, first, that 0.065 per cent, observed at flood stage in 1906, represents the normal tribute from other sources than mining, and, second, that the mines contributed the same total amounts at low and high stages in 1879 (discharges being 510 and 18,000 ft.^{3}/sec.), and if we base on these assumptions a computation of the low stage percentage of load in 1879, we obtain an estimate of 12.6 per cent, which is 14 times greater than the observed load, 0.86 per cent. The discrepancy is altogether too great to be accounted for by errors in the explicit assumptions, and its explanation involves the factor of competence. The stronger currents of flood stages were competent to suspend heavier particles than were the feeble currents of low stages, and so a part of the load which at high stages reached the mouth of the river at Marysville was at low stages arrested on the way, being deposited in the low-water pools.

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[1] Manson, Marsden, Report of determinations of sediment held in suspension, etc.: California State Engineer Report, 1880, Appendix B.

In these cases it is evident that the range of available fineness is determined, through velocity, by discharge, and that the load of débris *within the range of adequate fineness* is determined by supply. The load appears to bear no relation to capacity, and if the term capacity be used in the broad sense of a stream's ability to suspend material of unspecified fineness, then it is undoubtedly true, not merely of the Yuba but of all rivers, that the suspended load is less than the capacity and depends for its quantity on supply. If, however, capacity be considered with reference to particular degrees of fineness, the case is somewhat different, for a stream may carry a full load of that material for which it is barely competent and at the same time have less than a full load of finer material, and the matter is further complicated by interdependencies in virtue of which each element of load tends to limit the capacity for all other elements of load.

To show the basis for these statements and also to explain certain mutual relations between traction and suspension, it is necessary to give somewhat elementary consideration to the subject of capacity for suspension.

As already mentioned and implied in various connections, the process of suspension depends on the diversity in direction of the strands of the current. If the lines of flow were parallel to the stream bed, as is sometimes assumed for the sake of simplifying mathematical discussions, there would be no suspension.[1] In the sinuous and swirling movements which characterize the flow of streams strands of current are continually passing upward and downward and are as continually dividing and blending. Particles of débris too light to resist the lower elements of the current are swept upward and are retained in the body of the stream through a process analogous to the stirring of the domestic pot. While thus incorporated they are impelled downward by gravity, and all but the

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[1] There is a theory originating with Dupuit (Études sur le mouvement des eaux, 1848) that suspension is due, or might be due in the ideal case of parallel flow lines, to reactions between solid particles and contiguous threads of current having different velocities. Under the postulate that the solid tends to move faster than the liquid, it is shown that the path of least resistance trends obliquely toward the swifter of adjacent threads of current, and therefore obliquely upward. As this theory retains place in current hydraulic literature, the fact that it is ignored in the text of the present paper may call for explanation. I do not accept the postulate and am of opinion also that the reasoning based on it ignores an essential factor. As a full statement and discussion of Dupuit's analysis would occupy much space, I will content myself with a statement of my own view. A good abstract of his theory, by E. H. Hooker, may be found in Am. Soc. Civil Eng. Trans., vol. 36, pp. 246–247, 320–322.

In various discussions of the subject the velocities are treated as "absolute"—that is, they are referred to the fixed walls and bed of the channel. As the only possible reactions between the solid particles and contiguous water are through relative velocities, it is better to focus attention on those by referring them to the center of the particle. Let us assume that the solid particle *A*, figure 70, is immersed in a current of which the parallel rectilinear filaments increase gradually in "absolute" velocity from below upward, and let us assume that at some instant it moves with the velocity and direction of the filament which is at the same level. Barring extraneous forces, it will continue indefinitely in the same direction and with the same velocity. The filament above moves, with reference to the particle, in a direction indicated by the arrow; the filament below moves in the opposite direction. Their relative velocities are the same, except for a possible difference of the second order of magnitude. The two filaments tend to draw the upper and lower parts of the particle in opposite directions, and the result is rotation. This is the only result dependent on the fact that the particle is solid. Now introduce the factor of density. The particle is denser than water. It is also part of a stream which is flowing, and the impulse it receives from gravity is greater than it would receive if it had the density of water. The component of gravity in the direction of flow, *AB*, acting on the excess of mass, draws the particle in the direction of flow. This component is proportional to the slope of the stream, which is a small fraction. At the same time the component of gravity normal to the direction of flow, *AC*, also draws the particle, which is equally free to move through the water in that direction. Its actual acceleration has the direction of their resultant, *AG*, which is vertically downward.

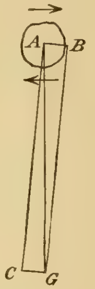

FIGURE 70.—Diagram of forces.

Dupuit's postulate was suggested and supported by the observed fact that a body floating down a stream moves faster than the visible current. Bérard demonstrated experimentally that the differential motion is due to the propulsion of the body by strands of current below the surface. See Annales des ponts et chaussées, 6th ser., vol. 12, pp. 830–835, 1886.

very finest actually move downward with reference to the surrounding water. From time to time they may touch the stream bed, but only to be lifted again by the next adequate rush of water.

Three ways are known in which the velocities of a stream are affected by the suspended load. In the first place, the load adds its mass to the mass of the stream, and as the stream's energy is proportional to the product of mass by slope, and the stream's velocity has its source in this energy, the addition tends to increase velocity. Second, the suspended particles are continually impelled downward by gravity. Also, as the strands of current containing them have curved courses, the particles are subject to tangential force, and because of their higher density this force is greater than the force simultaneously developed by the containing water, so that they are impelled through the water. Motion through the water, caused by these two forces, involves work; and this work is a direct consequence of suspension. The energy expended is potential energy, or energy of position, given to the particles by the flowing water, and its source is the energy of flow. So the work is the measure of the work of the stream in suspending the particles. It may therefore be regarded as a tax on the stream's energy, resulting in reduction of velocity. Third, the imperfect liquid constituted by the combination of water and débris is more viscous and therefore flows more slowly than the water alone. The solid particles do not partake of the internal shearing involved in the differential movements of the current, and by their rigidity they restrain the shearing of water in their immediate vicinity. Moreover, each particle is surrounded, through molecular forces, by a sphere or shell of influence which still further interferes with the freedom of water movement.

The relative importance of these factors varies with conditions, and no simple statement is possible because the influence of each factor follows a law peculiar to itself. The most important conditions affecting the influence of the mass of the load are discharge and slope, while for the work of suspension and for viscosity the important condition is the degree of comminution of the load.

The mass which the load contributes to the stream is equivalent, in relation to potential energy, to an increase of discharge, and its product by the stream's slope is proportional to potential energy in the same sense in which the stream's energy is proportional to the product of discharge and slope. In a series of experiments with loadless streams of water flowing in straight troughs, the mean velocity was found to vary approximately with the 0.25 power of the discharge and the 0.3 power of the slope. Under the particular conditions of these experiments

$$V_m = Q^{0.25}\, S^{0.3} \times \text{constant}.$$

Differentiating with reference to Q, we have

$$dV_m = dQ \times \frac{0.25\, S^{0.3}}{Q^{0.75}} \times \text{constant}.$$

The increment to Q being interpreted for present purposes as the suspended load, we see that the corresponding increment to mean velocity has a magnitude which varies directly but slowly with the slope and inversely but more rapidly with the discharge.

Each particle in suspension is drawn downward through the surrounding water by gravity. It is impelled through the water in an ever-changing direction by tangential force. The average speed of the resultant motions, referred to the surrounding water, is greater than the constant rate of descent the particle would acquire if sinking in still water. Therefore the work of suspension, measured by all the motions through the water, is greater than the work of simple subsidence, a quantity as to which much is known. The measure of a particle's work of subsidence per unit time is the product of its mass, less the mass of an equal volume of water, by its fall in unit time by the acceleration of gravity. If we call the mass of the particle M and its velocity of subsidence V_s, and assume its density to be 2.7, the measure of the work of subsidence is

$$\frac{1.7}{2.7} M V_s g = 0.63\, M V_s g$$

The coordinate measure of work for the stream's flow is the product of its mass by its fall in unit time by the acceleration of gravity, and the contribution which the particle, considered as a part of the stream, makes to the work of flow is therefore measured by the product of its mass by the fall of the stream in unit time by the acceleration of gravity. As the fall of the stream in unit time is equal to the mean velocity multiplied by the slope, the measure of the particle's work of flow is MsV_mg. This is a measure of the particle's contribution to the stream's energy, while 0.63 MV_sg is a coordinate measure of that factor of its draft on the stream's energy which depends on the direct action of gravity. The other factor of draft, the factor depending on tangential forces, varies with the violence of vertical movements and is of comparable importance only in the case of torrents. If we leave it out of account, the result of the comparison is that when 0.63 of the rate at which the particle is pulled through the water by gravity is greater than the rate at which it falls by reason of the general descent of the stream, its tax on the stream's energy is greater than its contribution thereto. Any allowance for the neglected factor would be equivalent to increasing the fraction 0.63.

To illustrate this relation by a concrete example: Mississippi River between Cairo and its mouth has, at flood stage, such velocity and slope that any suspended particle of silt which would sink in still water faster than half an inch a minute retards the current more through the work of suspension than it accelerates the current through the addition of its mass to the mass of the stream.

The velocity of subsidence has been elaborately studied. So far as river problems are concerned, it depends chiefly on the size of the suspended particles. For particles below a certain magnitude, which is controlled in part by impurities in solution, the velocity is zero. Between two critical diameters, which for quartz sand are about 0.02 and 0.5 millimeter[1] (0.00007 and 0.00016 foot) the velocity varies with the square of the diameter. Below the lower diameter the variation is more rapid, and above the upper it is less rapid, becoming for large particles as the square root of the diameter.

It follows that the consumption of energy involved in the suspension of the suspended load is an increasing function of the size of the particles into which the load is divided; in other words, it is a decreasing function of the degree of comminution. On the other hand, the contribution which it makes to energy by adding its mass to that of the water is independent of the degree of comminution.

The viscosity factor is not easily compared in a quantitative way with those just considered, but something may be said of the laws by which it is related to comminution. Attending first to that part which depends on interference with internal shearing of the water, let us conceive of a particle with center at C, figure 71, surrounded by water which is subjected to uniformly distributed shearing along planes parallel to $A_1AA_2B_2BB_1$, the direction of shearing being parallel to the line ACB. Conceive a right cylindroid figure tangent to the particle and parallel to AB, its bases being A_1HA_2G and B_1EB_2F. Motions being referred to C as origin, the cylindroid body of water would assume after a time, but for the presence of the particle, the form of the oblique cylindroid with bases $A_1H_1A_2G_1$ and $B_1E_1B_2F_1$.

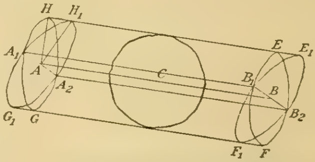

FIGURE 71.—Interference by suspended particle with freedom of shearing.

Because of the obstruction by the rigid particle the simple shearing motions thus indicated are replaced by other motions, components of which are normal to the shearing planes. It is assumed that the sum of the transverse elements of motion measures the action occasioned by the presence of the particle. The actual movements caused in the water doubtless affect regions within and without the cylindroid, but their nature need not be considered. The necessary transverse movements are equivalent to the transfer of a lunate wedge of water, $HA_1H_1A_2$ to a symmetric position on the opposite side of the plane $A_1A_2B_2B_1$ and a similar transfer of the wedge $FB_1F_1B_2$. Linear dimensions of the first-named wedge, in the direction of rectangular coordinates, are A_1A_2, HA, and HH_1. A_1A_2 equals a diameter of the particle. HA equals a semidiameter. As the angle HAH_1, being given by the general amount of shearing, is independent of the size of the particle, HH_1

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[1] Richards, R. H., Textbook on ore dressing, pp. 262-268, 1909.

equals $AH \times \tan HAH_1$ and is proportional to a diameter of the particle. On the assumption that the diameters of the particle are equal it follows that the volume of the wedge is proportional to that of the particle, or to D^3. The distance of the center of gravity of the wedge from the plane $A_1A_2B_2B_1$, being a linear dimension of the wedge, is proportional to D, and the mean distance of transfer, which is double that distance, is also proportional to D. The quantity of motion normal to the shearing planes, occasioned by the particle, is measured by the wedge of water times the mean distance of transfer, and, the mass of the wedge being proportional to its volume, the quantity of motion is proportional to $D^3 \times D = D^4$. The quantity of motion occasioned by the entire suspended load, all its particles being assumed to have the same size, is proportional to ND^4, where N is the number of particles; and if the mass of the total load remain unchanged while its degree of comminution is varied, it is evident that N varies inversely with D^3. Therefore the quantity of internal motion occasioned by a particular mass of suspended matter of uniform grain is proportional (since $D^4/D^3 = D$) to the diameter of its particles. The fundamental assumption of the analysis is that this motion measures a resistance to the freedom of the water which is coordinate with viscosity and which may for practical purposes be considered as an addition to the resistance arising from the viscosity of the water.

That portion of the viscosity factor which depends on the molecular influence of the particle outside its boundary is still less susceptible of quantitative estimate but may yet be discussed with reference to the diameter of the suspended particle. In ignorance of the exact nature of the influence and also of the law by which it diminishes with distance outward from the boundary, I assume arbitrarily that at all distances from the particle less than l the freedom of water molecules is restricted, and that the amount of restriction is measured by the volume of the space in which the restriction is experienced. The imperfection of this assumption will of course affect any deduction from it. That volume is $\frac{1}{6}\pi(D+2l)^3 - \frac{1}{6}\pi D^3$. For the entire suspended load, assumed to consist of N equal particles, the total volume is N times as great. For a load of invariable weight but variable comminution, $N \propto \frac{1}{D^3}$, and the total volume is proportional to

$$\frac{\frac{1}{6}\pi\left((D+2l)^3 - D^3\right)}{D^3}$$

or, introducing a constant, K, and reducing, we have

$$\text{Volume} = K\left(\left(\frac{D+2l}{D}\right)^3 - 1\right)$$

Evidently the influence of this factor varies inversely with D. When D is very large as compared to $2l$, it approaches zero; when D is small as compared to $2l$, it is relatively very great. It is most sensitive to the control by D when the particles are very small.

The two divisions of the viscosity factor vary in their influence on velocity with the comminution of the load but in opposite ways, the influence of the first being greater as the particles are larger and that of the second as they are smaller. The laws of variation are such that their combination exhibits a minimum—that is, for some particular size of particle the influence on velocity is less than for particles either larger or smaller.

Another mode of treating the viscosity factor assumes that, so far as the viscosity effect is concerned, the molecular influence is equivalent to an enlargement of each particle to the extent of l on all sides. Then, reasoning as before with reference to interference with shearing, we obtain

$$\text{Resistance} \propto \frac{(D+2l)^4}{D^3}.$$

This expression is not only simple but has the advantage of giving definite indication of the position of the minimum. The resistance is least when $D = 6l$.

We may now bring together the qualitative results of analysis, and write

$$V_{ms} = V_m + Wf_1(\acute{S}, \grave{Q}) - f_2(\acute{D}) - f_3(\breve{D})$$

This may be read: The mean velocity (V_{ms}) of a stream carrying a load of suspended débris of diameter D equals the mean velocity (V_m) of the same stream when without load, plus a factor due to the weight (W) of the load and varying directly with the slope and inversely with the discharge, minus a factor due to the work of suspension and varying directly with the diameter of particles, minus a factor due to viscosity and varying inversely with the diameter if the particles are minute and directly with the diameter if they are larger.

It was convenient in the discussion to regard the whole suspended load as of one grade, but the result may be applied to any individual particle. For the actual stream with diversified load the equation might be written

$$V_{ms} = V_m + Wf_1(\acute{S}, \grave{Q}) - \Sigma f_2(\acute{D}) - \Sigma f_3(\check{D}) \text{ . . } (111)$$

An investigation of the influence of suspended matter on viscosity has recently been made by Eugene C. Brigham and T. C. Durham.[1] The materials used by them were powders so fine that their tendency to settle in the water did not interfere with the conduct of the experiments. The work of suspension was therefore so small a factor as to be negligible. Various mixtures of water and powder were allowed to flow through a vertical capillary tube, impelled by their own weight, and the time of transmission for a determinate volume was noted. The time for a mixture containing 100 parts of water to 2.15 parts, by weight, of clay was found to be 15 per cent greater than the time for clear water; or the average velocity, within a slender tube, was reduced 15 per cent by the addition of the clay. If we assume the flow lines to have been parallel, as was probable, the theoretic increment of velocity due to the weight added by the clay was 1.6 per cent; if the flow lines were sinuous, the theoretic increment was less. The loss of velocity due to increased viscosity was therefore somewhat greater than 15 per cent and may have been as much as 16.6 per cent. Had the experiment been so arranged as to involve sinuous or turbulent flow, it would apply more cogently to the phenomena of rivers, but without that adjustment it serves to show that when the suspended material is exceedingly fine the loss of velocity through added viscosity is very much greater than the gain of velocity because of added weight.

The size of the particles was not reported, but the fact that the rate of settling was inappreciable suggests that their size may have fallen below that corresponding to a minimum influence on viscosity. Some light is thrown on this point by the results obtained with other fine powders. Interpolation from the reported data gives the following comparative estimates of the loss in velocity from the suspension of the same volumes of three substances: Infusorial earth, 3 per cent; graphite, 12 per cent; clay, 15 per cent. Of these the infusorial earth was coarsest, remaining in suspension largely because differing little in density from the water, while the graphite was a commercial variety said to be permanently suspended. An independent determination by L. J. Briggs and Arthur Campbell[2] gave a loss in velocity of 7 per cent, the material being a clay which "would not remain in a state of permanent suspension." The comparative data render it probable that the clay causing a retardation of 15 per cent was so finely divided as to give great effect to the molecular forces of the shell of influence.

The data from infusorial earth are useful in correlating the various factors which modify the stream's velocity. Assuming that the diatom tests composing the earth sample were similar to those figured in geologic textbooks, I have estimated the velocity of subsidence of particles having the same size but as dense as ordinary river silt and find that it corresponds to the critical velocity computed for the Mississippi at flood stage. That is, a suspended silt so fine as to have a large viscosity effect, so that a charge of 2.15 per cent reduces velocity by 3 per cent, is at the same time able, through its work of suspension, to consume all the energy it contributes to the current through its addition of mass. A finer silt would retard more by increasing viscosity, and a coarser silt would retard more through the work of suspension.

The available data are not fully demonstrative, but they render it highly probable that, under all conditions, streams are retarded by their suspended loads. If that be true, there is a capacity for suspension coordinate with capacity for traction. For each grade of suspended débris, and with any particular slope and discharge, it is possible by increasing the load so to retard the current that it is barely competent to suspend débris of that grade, and the stream is then loaded to its full capacity.

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[1] Am. Chem. Jour., vol. 46, pp. 278-297, 1911.

[2] Unpublished; communicated in letter.

In a natural stream the suspended particles are of many sizes, and all tend to reduce velocity. Some of the particles are near the limit of competence, and any increase of load will so reduce velocity that these can no longer be upheld. As to these coarsest particles the stream is loaded to full capacity, but not as to finer material. The addition of fine material will cause the arrest of some of the coarser, but will increase the total load. An exactly parallel statement may be made as to the tractional load.

To recur to the laboratory determinations of retardation by suspended material, it is of interest to note that the loads tested in the experiments, while greater than those ordinarily found in rivers, are representative of flood conditions in the more turbid streams. The load of 2.15 per cent, which caused retardations of 3 to 15 per cent, is equaled by ordinary floods of the Colorado of the West and is exceeded by ordinary floods of the Rio Grande and the Pecos. For the Rio Grande there are several records in the neighborhood of 10 per cent,[1] and small streams in arid lands are liable to receive similar loads as a result of violent local storms. On the other hand, the Mississippi near its mouth carries an average load of only 0.07 per cent, with a recorded maximum of 0.8 per cent.[2]

An attempt was made to measure the retardation of the current by tractional load. It was assumed that the bed resistance of a loaded stream has two parts, one due to the texture of the bed, the other to the work of traction, and that the reduction of velocity by traction could be measured by comparing speeds of loaded and unloaded streams on beds of the same texture and slope. A series of experiments were accordingly performed with unloaded streams flowing over beds composed of fixed grains of débris, or débris pavements, and it was thought that their mean velocities would be materially higher than those observed with streams otherwise similar but bearing loads. When the comparison was made, however, it was found that in 11 out of 16 experiments the observed velocities were higher with loaded than with unloaded streams; and the average of the 16 results was of the same tenor, ascribing a slight excess of velocity to the loaded streams. As the estimates of mean velocity had been based on observations of depth, and as the observations of depth were difficult in the case of loaded streams, it was thought possible that the result was affected by a systematic error in those depth measurements which had been made by means of the gage (p. 25). Examples were therefore sought in which the depth had been obtained by comparing the average height of the water surface during the run with the average height of the débris bed after the water had been drawn off. Thirteen instances were found in which such better-conditioned measures could be compared with measures of unloaded streams, and in 11 of the 13 comparisons the unloaded streams gave the higher mean velocities. The average of the 13 velocities found for loaded streams was 10 per cent less than the corresponding average for unloaded streams. The best of the available data, therefore, give evidence of the consumption of stream energy by traction, but the evidence is not so consistent as to free the matter from doubt. In Table 80 V_{ml} and V_{mu} represent the mean velocities of loaded and unloaded streams, and the various data are arranged according to the magnitude of the ratio of these velocities. This arrangement brings out the apparent fact that the reduction of mean velocity by traction is greater for small loads than for large, for gentle slopes than for steep, for low velocities than for high, and for large depths than for small. While it is entirely possible that such a result—a result opposed to my preconceptions—has been occasioned by a systematic error of observation, I am disposed to regard it rather as the expression of some physical law which has escaped my analysis. It is possibly connected with a fact brought out in the following chapter in the discussion of vertical velocity curves—the fact that addition of load has a pronounced influence on the distribution of velocities, increasing the contrast between velocities near the bed and the mean velocity.

If the variations of the load effect be ignored and attention given only to the means of quantities compiled in the table, it appears that 10 per cent average reduction of velocity corresponds to an average load of 148.5 gm./sec. per cubic foot of discharge, or 0.52 per cent, by weight, of tractional load.

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[1] U. S. Geol. Survey Water-Supply Paper 274, pp. 102–104, 1911.

[2] The average is on authority of Humphreys and Abbot (Physics and hydraulics of the Mississippi); the maximum is from an observation reported by J. A. Seddon (Rept. Chief Eng. U. S. A., 1887, p. 3094)—"231.9 grams per cubic foot."

Table 80.—*Comparison of mean velocities of streams with and without tractional load.*

[Width, 1.00 foot.]

Grade of débris.	Discharge.	Slope.	Load.	Duty.	Depth of unloaded stream.	V_{ml}	V_{mu}	$\frac{V_{ml}}{V_{mu}}$
	Ft^3 sec.	*Per cent.*	*Gm./sec.*	*Gm./sec.*	*Foot.*	*Ft./sec.*	*Ft./sec.*	
(D)	0.734	0.37	21	28.6	0.410	1.79	2.43	0.74
(D)	.734	.32	12	16.4	.411	1.79	2.35	.76
(D)	.363	.43	12	33.1	.229	1.97	1.97	.80
(B)	.363	.43	21	58.0	.193	1.88	2.29	.82
(D)	.363	.58	23	63.4	.199	1.82	2.15	.85
(B)	.363	.54	25	69.0	.176	2.03	2.39	.85
(D)	.363	.35	12	33.1	.224	1.62	1.87	.87
(D)	.545	.53	30	55.0	.240	2.27	2.46	.92
(B)	.734	.38	38	51.7	.267	2.75	2.92	.94
(B)	.734	.48	52	70.8	.256	2.87	3.03	.95
(B)	.734	.54	80	109.0	.241	3.04	3.10	.98
(D)	.363	2.11	258	711.0	.098	3.70	3.37	1.10
(D)	.363	1.94	229	632.0	.099	3.66	3.30	1.11
	....	....	....	148.5	....	....	....	.90

THE TWO LOADS.

The reaction of tractional load on velocity affects primarily and chiefly the zone of saltation, but there is also a general retardation of the stream. The reaction of suspended load reduces all velocities, including those of the tractional zone. Thus the magnitude of each load affects capacity for the other load, and it also affects the conditions of competence for suspension and competence for traction.

As all parts of the load influence velocity, so all parts influence the general slope of an alluvial stream, which is automatically adjusted so as to give to the discharge the ability to transport all the material, coarse and fine, which is supplied. The adjustment is actually made through the coarser material, for the permanent deposits of the stream bed are from the tractional load.

Along with the adjustment of slope goes an automatic partition of the varied load into suspensional and tractional. If the lower Mississippi, for example, were to be supplied for the future with only that part of its load which is now carried in suspension, it would so reduce its slope that the slackened current would drop a portion of that load and thereafter move it by traction. If, on the other hand, the river were to be deprived of the fine débris now carried in suspension, it would so quicken its current as to lift into suspension a portion of the débris now carried by traction and would adjust its slope in such way as to maintain the partition of load.

An exception to the general law of automatic partition is found when the load has only small range in fineness, and this was illustrated by the artificial conditions of the laboratory; but it is not known that natural streams illustrate the exceptional case.

This phase of river adjustment is well illustrated by Yuba River, which I studied in 1904–1908. Where it issues from the mountains it carried a heavy load of coarse débris with which it was building up its bed at the edge of the Sacramento Valley. A dam thrown across it in the region of deposition arrested the tractional load for a time and gave an opportunity, by the aid of measurements, to estimate its amount. There were also samplings of the water and measurements of suspended load. The tractional load consisted mainly of gravel, with coarse sand and many bowlders, and the suspended load during flood included sand and finer débris. Fifteen miles below, near the mouth of the river, the tractional load consisted of sand, with rare small pebbles, and only clay and silt were in suspension. Here, too, the load suspended at flood stage was estimated from a sampling of the water. A computation based on the various data indicated that at flood stages the suspended load was approximately equal to the tractional load at each of the two localities.[1] While the data for this estimate were imperfect in many ways, they were nevertheless better than any other with which I am acquainted.

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[1] A somewhat fuller statement may be found in Geol. Soc. America Bull., vol. 18, pp. 657–658, 1898.

Information as to suspended loads is fairly abundant, but there are no satisfactory data as to the complementary tractional loads.

The character of the partition of load depends in each particular instance on the relative proportions of the various grades in the débris with which the stream is supplied. It varies from point to point along the course of the same stream. In the case of Yuba River the variation was due to the fact that exceptional conditions created by hydraulic mining had thrown the bed profile out of adjustment; and many other streams are dealing with new and man-made conditions; but natural streams also have strongly contrasted load conditions in different parts of their courses. These arise, first, from the diversity of detritus furnished by tributaries, and, second, from the gradual comminution of the load as it is borne along.

The partition of load is greatly modified by variation of discharge and by temporary conditions of débris supply. A number of changes due to varying discharge have already been mentioned. The changes in velocity affect the grade of fineness marking the plane of partition. With reduction of discharge from a flood stage, the conditions of partition come to differ in pools and over shoals, and usually suspension ceases altogether, while traction is still continued on the shoals. With flood discharge, also, the partition is probably not quite the same for deep and shoal, a portion of the load traveling by suspension through the deeps but by traction over the shoals.

When a flood is occasioned by heavy rains the fine particles of soil are washed to the stream, with the result (1) that the suspended load is relatively large and (2) that the limiting grade is relatively fine. When an equal flood is caused by snow melting, without rain, the suspended load is smaller and the limiting grade coarser; in extreme cases there may be no suspension whatever. While a river is at low stage and without load, a local shower may wash to it a temporary supply of débris of which only the finer part will be immediately transported, giving suspension without traction.

The partition of load also varies greatly from point to point in the same cross section, competence for suspension and traction both responding to the control of velocity.

Despite these variable factors, it is quite possible that in the entire load of a stream large enough to be called a river there is a fairly definite ratio between suspension and traction. Knowledge of that ratio would be of practical importance to the engineer and geologist, because the measurement of the tractional load is always difficult, while measurement of the suspended load is merely a matter of routine and patience. The estimate afforded by the Yuba is a rough approximation and is qualified by the fact that the stream had not an established regimen but was engaged in adjusting its slope to new conditions of load.

Of other estimates of tractional load, the one most often quoted is that of Humphreys and Abbot. They found that the bar across one of the mouths of the Mississippi increased its width at the top at the rate of 338 feet a year and that the material added was similar to that of the tractional load. Assuming that the deposit had an outward extent to the depth of 100 feet and a transverse extent equal to the widths of all the mouths, they made a computation from which the tractional load was estimated at 11 per cent of the suspended load.[1]

An elaborate study of the loads of the Rhone was made by Adolphe Guérard,[2] who measured the suspended material by sampling the water for two years and computed the total output from the soundings of the sea bed, the survey of which had been repeated after an interval of 31 years. He found the suspended load less than one-fourth of the whole. Various partial estimates have been based on the march of subaqueous dunes. Where the volume of a dune and its rate of progression are known, their product determines definitely a part of the load, and if the data cover a year they yield at once a minimum estimate for the annual load. Some large dunes in various streams have been reported to persist from year to year, with progressive change of position, but Arthur Hider, who kept two tracts of the Mississippi channel under observation for about a year, found that the dunes were repeatedly readjusted in respect to size as the river stage changed, so that none could be identified through long periods, while the epochs of readjustment were characterized by general deposition or general scour, which could not be accounted for as a result of the dune transformations.[1] A similar remodeling was observed by Partiot in the Loire.[2] Hider estimated the whole movement in dunes as 14,800 cubic yards in 24 hours, which corresponds to 2.2 per cent of the average suspended load reported by Humphreys and Abbot; but his judgment was that the entire movement of débris along the bed was at least ten times as great as the movement in dunes.

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[1] Hydraulics of the Mississippi, p. 149.

[2] Inst. Civil Eng. Proc., vol. 82, pp. 308-310, 1885

As a generalization from extensive observations of dunes in the river Loire, Sainjon formulates their rate of advance when the material is sand as a function of surface velocity, V_s. In his equation [3]

$$\text{Advance} = 0.00013\ (V_s^2 - 0.11)$$

the units are metric. Substituting feet for meters, we have

$$\text{Advance} = 0.00004\ (V_s^2 - 1.18)$$

The associated average height of dune crests [4] is 0.77 meter, or 2.54 feet. As the mean height of a dune is approximately one-half the height of its crest, we may multiply the rate of advance by 2.54/2 and obtain

$$0.00005\ (V_s^2 - 1.18)$$

as an expression for the Loire's load of sand carried in dunes, for each foot of channel width occupied by dunes. In a later discussion by Lechalas (see p. 193) it is shown that Sainjon's formula does not apply to surface velocities above 3.3 ft./sec., the rate of dune advance being then checked because part of the sand escapes into the body of the current and is not added to the downstream faces of the dunes; but the observations on dunes constitute the quantitative basis of the formulation of débris transportation by Lechalas, of which an account is given in Chapter X.

In this connection mention may be made of moving sand bodies of a different order of magnitude and probably of a different type. They are greater than the dunes of the same stream and are coordinate in size with the bars separating deeps but are distinguished from the bars by their migration downstream. In some of the "regularized" streams of Europe, where the main channel is artificially restricted to curves of large radius, they are developed in systematic alternation at the two sides, and the thalweg winds between them.[5] In the Mississippi they sometimes appear in the reaches. Their progress downstream is accomplished by deposition on forward slopes and erosion of rear slopes, but the forward slopes are not steep, like those of dunes, and their material is not wholly derived from the tractional load. Blasius [6] regards them as essentially dunes, correlating them specifically with dunes of reticulated pattern. My own view, not necessarily inconsistent with his, connects them with the fixed bars separating the deeps of a meandering stream. A free stream does not tolerate a straight channel. If a straight channel of moderate width be given to a stream, the current swings rhythmically to right and left, and if the banks yield it develops meanders. The meanders then migrate, according to laws of their own, and the bars are fixed in relation to the meanders. If the banks do not yield, the system of shoals and deeps established by the swinging current migrates slowly downstream. It is evident that the migration of these shoals is one of the factors—and may be an important factor—in the work of transportation; and also that every measurement of the migration of a shoal is a partial measurement of load.

Pilots of Mississippi steamboats observe that the bars at crossings are built up by floods, and such changes have been measured by engineers. The generalization has sometimes been made that deposition is a specific function of floods, but a more satisfactory interpretation is given by McMath,[7] who maintains that the rising river scours from the deeps to deposit on the shoals, and the falling river scours from the shoals to deposit in the deeps. The transfers are the joint work of traction and suspension. As such changes of the stream bed are measurable they afford quantitative data as to load, and it was from their observation that Hider, as previously quoted, inferred that the dune movement in the Mississippi includes but a small fraction of the tractional load.

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[1] Mississippi River Comm. Rept. for 1882, pp. 80–88. Observations by W. H. Powless, made at a different place and in another year, are of the same tenor. See idem for 1881, pp. 66–120.

[2] Annales des ponts et chaussées, Mém., 5th ser., vol. 1, p. 270, 1871.

[3] Quoted, with some of the data, by Partiot, idem, pp. 271–273. The coefficient is there erroneously given as 0.0013.

[4] Given by Lechalas in the same volume, pp. 387–388.

[5] Engels, H., Zeitschr. Bauwesen, vol. 55, pp. 664–680, 1905.

[6] Idem, vol. 60, pp. 465–472, 1910.

[7] Mississippi River Comm. Rept. for 1881, p. 252.

The dune movement, the migrations of greater bars, and the transfers of débris from deep to shoal and shoal to deep are all competent to give information as to tractional load, but the estimates they give are minimum estimates, to be supplemented by estimates of the material which at flood stages is swept steadily along without contributing to any of the temporary deposits in such way as to be accessible to measurement.

AVAILABILITY OF LABORATORY RESULTS.

THE SLOPE FACTOR.

We are now ready to inquire whether, in view of the diversities and complexities affecting traction by natural streams, the formula for tractional capacity derived under the comparatively simple conditions of the laboratory is of practical value in connection with natural streams. The four factors of the formula may first be considered separately.

The general slope of a stream is the quotient of fall by distance, the distance being taken along the stream's course. It is best measured at high stage, because the chief work of grading the channel is accomplished by floods.

With reference to variations in capacity at a single locality, slope does not enter, the variations being referred to discharge; but account must be taken of slope in comparing different divisions of the same stream and in comparing one stream with another.

In all such cases the stream's slope is as definite a quantity and is susceptible of as precise measurement as is the slope of the laboratory channel. It differs as to its representative character. The laboratory slope is connected with a single discharge and a single grade of débris of determinable fineness. The slope of the natural stream does not represent the adjusting work of a determinable discharge but is a compromise product of the work of many discharges, and it is usually true that the velocities associated with these discharges have determined equally diverse mean finenesses of débris. The work of the natural stream, moreover, has been characterized by greater diversity, from point to point, of the bed velocities, and its system of velocities has been regulated in part by suspended load.

These difficulties would prove insuperable if attempt were made to infer the capacity of a natural stream from that of a laboratory stream, but they are not necessarily important in transferring a law of variation from a group of laboratory streams to an equally harmonious group of natural streams. If the diversification of discharges and finenesses is of the same type for the examples of natural streams between which comparison is made, it may well be that the slopes are comparable, one with another, in the same sense in which they are comparable in laboratory work, and that their relations to capacity should follow the same law.

THE DISCHARGE FACTOR.

Discharge differences must be considered when the tractional capacities of different streams are to be compared, and also in comparing the capacities of the same stream at different times.

In making comparison between different streams it is important that the discharges used be coordinate—that is, that they represent equivalent phases of stream work. If coordination be not secured, allowance must be made in one stream or the other for the variation of capacity with stage. In case the problem is such that the choice of phase is optional, preference should be given to flood phases, because the general slope and the details of channel shape are approximately adjusted to such phases. The greatest known discharge is probably less representative of the channel conditions than is the mean of annual maxima of discharge. It is believed that with use of discharges that are both representative and coordinate the discharge factor of the empiric formula may be applied. The result of such application will be the more satisfactory in proportion as the streams compared are allied in type and will be relatively unsatisfactory for streams in different climatic provinces or for comparison of a direct alluvial stream with one which meanders.

It is to be observed that in all studies of alluvial streams the discharge of which account should be taken in connection with traction is the discharge flowing in the channel proper. That which passes the banks ceases to contribute of its energy to the work of traction, and the portion of load diverted with it is not tractional.

The case of variation of discharge in the same stream is complicated by simultaneous variations of fineness and competence. In the experiments with sieve-separated grades of débris fineness and competence were constants with reference to discharge; but in a natural stream, where the tractional load may have great range in fineness, the mean fineness of the load varies with discharge, and the reason of its variation is that competence varies with discharge. The two competences which limit the range in fineness move up and down as discharge changes, and the mean fineness moves with them. Therefore the response of capacity to discharge can not be considered by itself.

For convenience in analyzing the conditions, let us assume first a discharge which is adjusted to the details of channel form, to the deeps and shoals. If, now, the discharge be increased, and with it the whole system of velocities, transportation will be everywhere stimulated, part of the tractional load will join the suspended, and the scouring of the deeps will bring into the tractional load a greater proportion of the coarser elements of the load. The mean fineness of that load will be reduced, and the capacity, while enlarged by increase of discharge, will be somewhat reduced by loss of fineness. The increase with discharge will be less than if the fineness were constant.

If, on the other hand, the discharge be reduced, some of the coarser material comes to rest, while finer débris is added from the suspended load. So the reduction of capacity from diminished discharge is qualified by the effect of increased fineness. But before the change in discharge has gone far the deeps become pockets for the reception of deposits, and traction is restricted to the intervening shoals, where it causes erosion. The erosion is selective, leaving an ever-increasing assemblage of residuary coarse material, which tends to protect the finer. The current on the shoals no longer obtains a full supply of the material for which it is competent, and the load and capacity part company. Or we may say that as the erosion of the shoals progresses the mean fineness of the accessible débris is reduced until a grade is reached for which the current is not competent. In either case the decadence of traction follows a law which is not well represented by the discharge term of the laboratory formula.

The above analysis postulates a wide range and somewhat equable distribution of fineness in the débris of the stream bed, a condition not always found. It might not apply, for example, to a stream which drains a district of friable sandstone and is therefore supplied with nothing coarser than sand. Nor would it apply well to a stream supplied with very coarse and very fine débris but not well supplied with intermediate grades.

In most alluvial streams, and probably in all meandering streams, the work of traction which is accomplished on the shoals at low stage and midstage is almost negligible in comparison with the high-stage traction. Not only is the rate of traction slow, but the field of traction is restricted. If a single formula will not fit both low and high stages, the one adjusted to high-stage variations will have the greater practical value.

Yet another consideration enters here, and one of peculiar importance. When discharge is reduced, and the competence of the current for traction is thereby changed, the coarse material eliminated from the tractional range ceases to be transported; but when discharge is increased, and the competence of the current for suspension is thereby changed, the fine material eliminated from the tractional range continues to be transported. It is, in fact, transported more rapidly, so that a greater amount passes a given section each second. For most or all practical purposes the change in mode of transportation is of no moment, and those purposes would be served by a formula which should include the material shifted and ignore the change in mode. In the system of reactions set up by change of discharge the two modes of transportation are so interwoven, in fact, that the practical discrimination of the suspended and tractional loads is impossible. Even in the laboratory experiments devised specially for the study of traction a certain amount of interplay was tolerated, for temporary suspension appeared over the crests of some of the antidunes and also in the bends of the crooked channels.

If the purely tractional point of view is to be exchanged for another, what shall be substituted? One natural suggestion is to include in a single view the entire load, suspended and tractional; another to include along with the tractional only that part of the suspended load which for part of the time is tractional also. That which would be included in one view and excluded from the other is the finer part of the suspended load, the part that does not sink to the bottom so long as the current is sufficiently active for traction. Being purely suspensional, its quantity is peculiarly a function of supply and is connected with discharge only through the association of discharge with rain. Wherever discharge is largely a matter of tribute from snowbanks, the suspended load is conspicuously independent of discharge.

If we exclude from view the purely suspensional material, a natural criterion for inclusion is the finest débris which low-stage discharge moves by traction, and as low-stage traction is limited to the bars, or interpool shoals, it is the finest tractional débris of those shoals. If we consider a gradual increase of discharge from least to greatest, we have at first no traction. Then for a particular discharge, which may be called the competent discharge, traction begins on the shoals, only the finest of the débris being moved. Gradually coarser and coarser material is included, the range in fineness and the load increasing together; but in this phase of action the load is not necessarily the equivalent of the capacity, for it may be limited by the supply of débris of requisite fineness. After a time another critical discharge is attained, which initiates the loaning of débris from traction to suspension, and thereafter a constantly increasing share of the traveling débris is suspended. As the suspended particles travel faster than the saltatory, and as capacity is the ability of the stream, measured in grams per second, to move débris past a sectional plane, the transfer from traction to suspension is an important factor in the enhancement of capacity.

The relation of capacity to discharge, contemplated from this viewpoint, has two elements in common with the discharge factor of the laboratory formula. It includes a competent discharge, corresponding to the zero of capacity, and it associates continuous increase of capacity with continuous increase of discharge. It differs, however, in important ways, and the possibility of expressing it by a definite formula is not evident. In the pool and rapid phase of activity the supply of débris suitable for traction is usually limited, and in many streams it is exhausted during each recurrence of the phase. In the phases of greater discharge, when traction occurs in the deeps as well as on the shoals, the sequence of capacities depends not only on discharge but on the relative proportions of débris of different grades of fineness in the material of the load. It is probable that for most streams the load-discharge function is discontinuous at the limit of the pool and rapid phase.

Because of this presumable discontinuity, because the tractional work while the pools exist accomplishes only a local transfer of débris, and because the work performed is usually of negligible amount in comparison with the work of larger discharges, it is probably better to ignore altogether the pool and rapid phase in any attempt at general formulation. If that be left out of account and if the general features of the laboratory formula be retained, the constant κ becomes the discharge which initiates traction in the deeps, and thus initiates *through* transportation of bottom load. If we accept that as a starting point, the material so fine as to be suspended by that discharge may be classed as purely suspensional, and other material suspended by larger discharges may be grouped with the tractional load. For the tractional load thus enhanced, or the *amplitractional* load, as it may conveniently be called, the rate of variation with discharge is evidently higher than the rates found for simple grades in the laboratory, and it may be much higher, for the débris diverted from traction to suspension, instead of lagging behind the lowest and slowest threads of the current, now speeds with the current's mean velocity.

It is possible that a practical formula for the fluctuations of an alluvial river's load may follow these lines, taking the form

$$C_a = b_3(Q - \kappa_1)^o \qquad (112)$$

where C_a is the capacity for amplitractional load, and κ_1 is the smallest discharge competent to establish a continuous train of traction through deeps and shoals; but the suggestion as to form has no better basis than analogy, and no data are known tending to determine the magnitude of the important parameter *o*.

THE FINENESS FACTOR.

When the work of two natural streams is compared and the streams are of the same type, it is believed that the fineness factor of the laboratory formula is applicable. It is true that fineness enters in a relatively complex way into the determination of the loads of natural streams, but for the comparison indicated the elements of influence are severally represented by the experiments, and their totals should follow a law of the same type. For small discharges this inference is subject to certain qualifications, which will appear from what follows.

When the work of the same stream is compared under different discharges, a difference in fineness is developed under the laws of competence. With larger discharge the mean fineness is less than with small discharge, and the difference in fineness conspires with the difference in discharge to determine capacity. For reasons explained in the last section, however, capacity can not always be considered synonymous with load when the discharge is small.

THE FORM-RATIO FACTOR.

In the reaches of a direct alluvial stream there is approximate uniformity of depth at high stage, and the conditions involving form ratio are essentially like those realized in the laboratory. To such cases the principles developed in the laboratory studies should be applicable.

It is true in a general way, as already mentioned on page 223, that at a high stage of a natural stream the sectional area is about the same for the reaches as for the bends, and so too is the width. It follows that the mean depth is about the same, although the maximum depth may be very different. The high-stage capacity is also the same at every section, after the channel form has been adjusted to the discharge. If these generalizations are correct, the principle involved in the form-ratio factor of the laboratory formula is applicable to curving streams, provided form ratio is interpreted as the ratio of mean depth to width, and not as the ratio of maximum depth to width.

In the analysis of conditions determining the relation of capacity to form ratio (Chapter IV) an important rôle was ascribed to the resistance of the banks; and the quantity of that resistance was represented in one of the parameters of the formula, α. The optimum form ratio, ρ, was found to vary inversely with α and, therefore, to vary inversely with the resistance of the banks. The resistance afforded by river banks is greater than that given by the smooth walls of laboratory channels, and this element tends to make the optimum form ratio relatively small for rivers. Its influence, however, is overshadowed by those of slope and discharge. As the optimim ratio varies inversely with slope, and as most rivers have lower slopes than the experimental streams, the general tendency of the slope element is to make the ratio large for rivers. As the optimum ratio varies inversely with discharge, and as the discharges of natural streams are relatively large, the tendency of this element is to make the ratio small for natural streams. The rates of variation being unknown, the net result of the three influences can not be inferred deductively. The data from Yuba River, cited in Chapter IV (p. 135), show that for one case of a natural stream the optimum ratio is decidedly larger than that established by the stream in its alluvial phase and is of the order of magnitude of the determinations made in the laboratory.

THE FOUR FACTORS COLLECTIVELY.

The results of the preceding discussions admit of a certain amount of generalization. When different streams of the same type are compared, and especially when the type is alluvial, the law of their relative capacities at high stage may be expressed by the laboratory formula (109). The ability of that formula to express the variation of capacity with discharge in the same stream is problematic.

It has not been shown that the system of numerical parameters determined for laboratory conditions can be used in extending the application of the formula to natural streams. If the formula were rational, the result of an adequate mathematical treatment of the physical principles involved, the constants measured in the laboratory would be of universal application (with moderate qualification for the conditions imposed by the curvature of natural channels); but the constants of an empiric formula afford no basis for extensive extrapolation.

THE HYPOTHESIS OF SIMILAR STREAMS.

When the Berkeley experiments were planned it was assumed that the relations of capacity to various conditions would be found to be simple, and that the laboratory streams were representative of natural streams except as to the characters associated with bending channels. Because of the discovered complexity of the laws affecting capacity it is now apparent that the laboratory formulas can not be applied to streams in general. It is, however, probable that among the great variety of natural streams there is a more or less restricted group which is in such respect similar to the laboratory group that the empiric results of the laboratory—or at least the results embodied in exponents—may properly be applied to it.

The criteria of similarity between large and small have been discussed to some extent by others in connection with the investigation of hydraulic problems by means of models. William Froude inferred from theoretic considerations that if the speed of a ship and the speed of its miniature model "are proportional to the square roots of the dimensions, their resistances at those speeds will be as the cubes of their dimensions,"[1] and he afterward verified this result by experiments. T. A. Hearson, in projecting a model river for the investigation of various hydraulic problems, discussed separately the resistance to flow by the wetted perimeter, the influence of varying sectional area, and the influence of bends. He concluded that if the linear dimensions were kept in the same proportion, so that the river channel and its model were similar in the geometric sense, the velocities would be related as the square roots of the linear dimensions, and the discharges as the 2.5 powers of the linear dimensions. It would be necessary that the roughnesses of the channel surfaces have the same differences as the linear dimensions, and that the movable débris of the bed also follow the laws of linear dimensions.[2] His deductions were not tested by the construction and use of a model, but they derive a large measure of support from the verification of Froude's analogous theorem. So far as I am aware, all the models actually constructed to represent rivers and tidal basins have been given an exaggerated vertical scale.[3] O. Reynolds [4] made a series of models of tidal basins in which the scales of depth and of tidal amplitude were greater than the scale of length, the ratios ranging from 31:1 to 105:1. No adjustment was made as to size of débris, the requirements of his investigation being met by any material fine enough to be moved by the currents. A tidal oscillation was communicated to water resting on a level bed of sand, with the result that the bed was gradually molded into shapes more or less characteristic of estuaries. From general considerations a "law of kinetic similarity" was deduced:

$$\frac{p\sqrt{h}}{L}=\text{constant}$$

in which p is the tidal period, h the depth of water (proportional to the amplitude of the tide), and L the length of the estuary. Under this law the results were generally consistent, but there was found to be a limit to the range of suitable conditions, and this limit was formulated by

$$h^3e=\text{constant}$$

in which e is the exaggeration of the vertical scale.

Eger, Dix, and Seifert,[5] making a model of a portion of Weser River for the purpose of studying the effect of projected improvements, adopted 1:100 as the scale of horizontal dimensions and depths, and 1:6.7 as the scale of mean diameters of débris particles composing the channel bed. It was then a matter, first of theory and computation but finally of trial, to select scales for discharge and slope. The main condition to be satisfied was that for discharges corresponding to high and low stages the depths of water should be properly related, according to the scale of linear dimensions. For the scale of discharges 1:40,000 was finally adopted, and for slopes 650:1. The resulting ratio of velocities was 1:4; and this ratio, combined with the ratio of débris sizes, was found to give a time ratio (for the accomplishment of similar changes in the bed of the stream) of 1:360. The scale of velocities being only 1:4 while the scale of distances was 1:100, there was an exaggeration of velocities in the ratio of 25:1.[6]

The quantities of débris moved being in the ratio of $1:100^3$, the distances moved in the ratio of 1:100, and the times consumed in the ratio of 1:360, the ratio of loads (per second) was $1:\frac{100^4}{360}$ or 1:280,000. The results were satisfactory; it was found that the successive forms given to the river bed by variations of discharge were repeated in the model.

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[1] These words are quoted from Inst. Naval Arch. Trans., vol. 15, p. 151, 1874. I have not seen Froude's original discussion of the subject.

[2] Inst. Civil Eng. Proc., vol. 146, pp. 216–222, 1900–1901.

[3] See Fargue, L., La forme du lit des rivières à fond mobile, pp. 57, 128, 1908. Fargue recommended for a model river a vertical scale of 1:100 and a horizontal scale of 1:20, from which he deduced a discharge ratio of 1:3,200 and a velocity ratio of 1:16.

[4] British Assoc. Adv. Sci. Repts. 1887, pp. 555–562; 1889, pp. 328–343; 1890, pp. 512–534; 1891, pp. 386–404.

[5] Zeitschr. Bauwesen, vol. 56, pp. 323–344, 1906.

[6] So stated by the authors. An allowance for the general principle that velocities are proportional to the square root of the hydraulic mean depth, and therefore to the square root of linear dimensions, would indicate 1:10 as the normal ratio of velocities, and give 2.5:1 as the exaggeration.

The exaggerations of the vertical scale by Reynolds and of the slope by Eger, Dix, and Seifert had the important effect of shortening the time necessary to produce the desired remodeling of the mobile bed. The absolute proportionality adopted by Froude and recommended by Hearson would have entailed a prohibitive consumption of time and might have added a serious complication in connection with the use of very fine débris.[1]

The similarity controlled by Reynold's law was a relation between the wave periods and dimensions of tidal basins and is not closely related to similarity in the control of tractional load. The similarities obtained in constructing the model of the Weser are more in point, because they involve an average rate of movement of débris; but they throw no light on the laws of variation of débris movement, which is the important matter in bridging the interval between our experiment streams and natural streams. After attempting to use various suggestions which came from the adjustments of the Weser model, I have returned to the principles of geometric similarity employed by Froude and Hearson.

Let us assume, as possible or plausible, that the principles developed in the laboratory, together with all parameters which are of the nature of ratios, are independent of the scale of operations and may be applied to streams of far greater magnitude, provided all linear factors are magnified in equal degree. If width and depth are enlarged in the same ratio, the form ratio is unchanged. If longitudinal distance and loss of head are enlarged in the same ratio, the slope is unchanged. If the dimensions of the transported particles are enlarged in the same ratio as the linear elements of channel, the linear coarseness is increased, or the linear fineness is reduced in that ratio.

The natural streams which may be considered as similar to the experimental streams constitute a class of moderate size. The form ratio for rivers ranges lower than for experimental streams, but there is some overlap. The smaller of the form ratios of the laboratory are representative of a considerable number of rivers. The slopes of rivers range lower than for laboratory streams, but here again there is overlap, and the natural streams which are similar in respect to slope are in general such as have coarse débris, so that there may be correspondence in that regard also. The similar natural streams to which hypothesis extends the laboratory results are those of large form ratio and steep slope, carrying coarse débris.

The primary difference between a large stream and a small one being one of discharge, and our general inquiry being directed to the valuation of capacity for traction, let us seek an expression for the relation of capacity to discharge when similar streams of different size are compared.

The laboratory data determine control of capacity by slope, discharge, fineness, and form ratio. In similar streams slope and form ratio are constant, and we need consider here only discharge and fineness. As we are comparing the laboratory streams as a group with similar natural streams, also taken as a group, it is advisable to employ a mode of formulation which lends itself to the use of averages, and the most convenient is that of the synthetic index. In

$$C \propto Q^{I_{3a}} F^{I_{4a}}$$

I_{3a} and I_{4a} are average values of the synthetic index and may be estimated, from data in Tables 32 and 43, as 1.32 and 0.77. Designating elements of the larger and smaller streams severally by subscripts $_{,,}$ and $_{,}$, we have, from the above,

$$\left.\begin{aligned} C_{,,} &\propto Q_{,,}^{1.32}\ F_{,,}^{0.77} \\ C_{,} &\propto Q_{,}^{1.32}\ F_{,}^{0.77} \\ \frac{C_{,,}}{C_{,}} &= \left(\frac{Q_{,,}}{Q_{,}}\right)^{1.32} \left(\frac{F_{,,}}{F_{,}}\right)^{0.77} \end{aligned}\right\} \quad \ldots\ldots \quad (113)$$

If we designate by L the ratio between a linear dimension of the larger stream and the corresponding dimension of the smaller.

$$\frac{d_{,,}}{d_{,}} = \frac{w_{,,}}{w_{,}} = L, \text{ and } \frac{F_{,,}}{F_{,}} = \frac{1}{L}$$

Calling mean velocity V, bearing in mind that the hydraulic mean radius is a linear dimension of channel, and recalling that the Chezy formula makes V vary as the square root of the hydraulic radius, we have

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[1] Such considerations as these affected the selection of materials for the Berkeley experiments and prevented the employment of very gentle slopes.

$$\frac{V_{\prime\prime}}{V_{\prime}}=L^{0.5}$$

Then, since discharge is the product of width, depth, and velocity,

$$\frac{Q_{\prime\prime}}{Q_{\prime}}=\frac{w_{\prime\prime}}{w_{\prime}}\times\frac{d_{\prime\prime}}{d_{\prime}}\times\frac{V_{\prime\prime}}{V_{\prime}}=L\times L\times L^{0.5}=L^{2.5} \quad \text{- - -}(114)$$

whence

$$\left(\frac{Q_{\prime\prime}}{Q_{\prime}}\right)^{-0.40}=\frac{1}{L}=\frac{F_{\prime\prime}}{F_{\prime}}$$

and

$$\left(\frac{F_{\prime\prime}}{F_{\prime}}\right)^{0.77}=\left(\frac{Q_{\prime\prime}}{Q_{\prime}}\right)^{-0.31}$$

Substituting this value of the fineness factor in (113), and reducing, we have

$$\frac{C_{\prime\prime}}{C_{\prime}}=\left(\frac{Q_{\prime\prime}}{Q_{\prime}}\right)^{1.01} \quad \text{- - - - - - - - - -}(115)$$

The result indicates that

$$\frac{C_{\prime\prime}}{C_{\prime}}=\frac{Q_{\prime\prime}}{Q_{\prime}}$$

whence

$$\frac{C_{\prime\prime}}{Q_{\prime\prime}}=\frac{C_{\prime}}{Q_{\prime}}$$

or, since $\frac{C}{Q}=U$, the tractional duty of water,

$$U_{\prime\prime}=U_{\prime}$$

That is, *for similar streams the tractional duty of water is the same.*

As the exponents connecting capacity with discharge, capacity with fineness, and mean velocity with hydraulic radius are all averages of low precision, the result is far from being so secure as might be inferred from equation (115). Its best support is really found in the plausibility of its conclusion. Our experience with a variety of physical laws makes it easy for us to believe that with suitable parity of conditions a unit of discharge will accomplish the same work as part of a large stream that it will accomplish as part of a small stream; and so the conclusion is plausible. The fact that an attempt to test the hypothesis of similar streams by combining it with experimental data has led to a plausible result is a fact favorable to the hypothesis.

Let us now assume the hypothetic law to be a real law and draw such inferences as may be warranted. The range of slopes which the experiments treat with confidence is from 0.5 to 3.0 per cent. Direct application is limited to streams having slopes within that range. By postulate,

$$\frac{D_{\prime\prime}}{D_{\prime}}=\frac{F_{\prime}}{F_{\prime\prime}}=L$$

Substituting in equation (114), we have

$$\frac{Q_{\prime\prime}}{Q_{\prime}}=\left(\frac{D_{\prime\prime}}{D_{\prime}}\right)^{2.5}$$

whence

$$\frac{Q_{\prime\prime}}{D_{\prime\prime}^{2.5}}=\frac{Q_{\prime}}{D_{\prime}^{2.5}}$$

That is to say, for similar streams, the ratio $\frac{Q}{D^{2.5}}$ may be regarded as constant. This relation affords a criterion for the discrimination of those natural streams which are similar to the laboratory streams, provided they are also similar in slope and form ratio. The following limiting values for $\frac{Q}{D^{2.5}}$ for different slopes are all estimated on the assumption of a form ratio of 0.05:

Slope (per cent).	Limiting values of $\frac{Q}{D^{2.5}}$.
0.5	3,000,000–40,000,000
1.0	2,000,000–30,000,000
2.0	1,500,000–10,000,000
3.0	500,000– 4,000,000

The form ratio 0.05 is considerably below the average of the ratios developed in the laboratory, and it is also much above the average for alluvial rivers at flood stage. Any allowance which might be made for this discrepancy would have the effect of increasing the estimate of limiting values of the ratios of Q to $D^{2.5}$. Subject to this qualification the ratios indicate the types of natural streams which are "similar" to the laboratory streams and to which various laboratory results may be applied. The streams are in general either small creeks or else rivers transporting very coarse débris. As the slopes are determined by flood discharges, such discharges should be used in the classification.

For the streams thus classified as similar to laboratory streams the duty of water is of the same order of magnitude, and so are the rates of variation of duty with the several conditions of slope, discharge, and fineness. The rates of variation apply especially to comparisons of one stream with another. For the estimation of variation with discharge in the same stream something should be added to the laboratory rate to allow for the varying assistance which suspension gives to the work of traction (p. 234). For estimation of optimum form ratio something should be deducted from the laboratory indication to allow for the greater resistance of the channel walls.

SUMMARY.

Natural streams of alluvial type differ from the streams used in the laboratory in ways connected with the bendings of their courses and with variations of discharge. The differences affect forms of cross section, the distribution of velocities within the section, and the partition of the load between suspension and traction. The two portions of load are carried at the expense of the stream's energy, each reduces the velocity, and the reduction of velocity determines the limit of carrying power. The whole burden of the stream includes not only two divisions distinguished by mode of transportation but as many minor divisions as there are grades of débris, and the load carried of each grade reduces the capacity for all the grades.

These and other complexities make it difficult to apply the laboratory results to natural streams. It is probable that the forms of the laboratory formulas are applicable, with limitations, to the comparison of one stream with another, but the availability of the exponents is problematic. There are special difficulties in attempting to use the formulas for the comparison of capacities of the same stream at different stages, and in such comparisons the tractional load can not be considered by itself, because much material which is swept along the bed at lower stages is lifted by flood velocities into the body of the current.

It is thought that the laboratory formulas may be applied to natural streams which are geometrically similar to the laboratory streams—that is, to streams having the same slopes and form ratios and carrying débris of proportionate size. The class of streams to which the formulas apply by reason of similarity is necessarily restricted, being characterized in the main by high slopes and coarse débris. It can include few large streams.

CONCLUSION.

It was a primary purpose of the Berkeley investigation to determine for rivers the relation which the load swept along the bed bears to the more important factors of control. As a means to that end it was proposed to study the mode of propulsion and learn empirically the laws connecting its output with each factor of control taken separately. The review of results in the present chapter shows that the primary purpose was not accomplished. In the direction of the secondary purpose much more was achieved, and a body of definite information is contributed to the general subject of stream work. A valuable outcome is the knowledge that the output in tractional load is related to the controlling conditions in a highly complex manner, the law of control for each condition being qualified by all other conditions.

With the aid of the Berkeley experience it would be possible to avoid certain errors of method and arrange experiments which should yield more accurate measurements of the same general class—and it is natural that the experimenter should feel the desire to do his work over in a better way—but I am by no means sure that adequate advantage would reward a continuance of work on the same or closely related lines. The complex interactions could be given better numerical definition, but it may well be doubted whether their empiric definition would lead to their explanation. It is possible that the chasm between the laboratory and the river may be bridged only by an adequate theory, the work of the hydromechanist. It is possible also that it may be practically bridged by experiments which are more synthetic than ours, such experiments as may be made in the model rivers of certain German laboratories. (See p. 16.)

The practical applications for results from experiments in stream traction belong almost wholly to the field of river engineering. For the transportation of detritus and related materials by artificial currents, stream traction will rarely be used, because flume traction is more efficient. Our results in flume traction have therefore an immediate practical application, and as they were limited in range the advantage of extending them can hardly be questioned.

The report on the Berkeley investigation properly closes with this chapter, but there are several by-products which seem worthy of record. Some of them are presented in the following chapter, and others are contained in appendixes.

CHAPTER XIV.—PROBLEMS ASSOCIATED WITH RHYTHM.

RHYTHM IN STREAM TRANSPORTATION.

This chapter is concerned with certain problems upon which the Berkeley investigation touched, but which were not seriously attacked.

The low precision of the observations on stream traction, a precision characterized by an average error of about 11 per cent and an average probable error after adjustment between 2 and 3 per cent, had for its chief cause the failure to eliminate from the experiments the influence of rhythm. The slope of the water surface, the slope of the channel bed, and the load of débris transported were all subject without intermission to rhythmic fluctuations. If materially better observations of the same sort are to be made, this difficulty must be successfully dealt with, and the first step toward mastering it is to understand it. The removal of a difficulty, however, is neither the sole nor the most important result to be expected from the study of tractional rhythms. Underlying them are physical principles which are of importance in the dynamics of rivers, and their study constitutes one of the available lines of approach to the broader subject.

For their empiric study the general plan of the Berkeley apparatus is well adapted, but our experience indicates that certain details should be modified. The use of a long trough is advisable, with contraction at the outfall, and with delivery of the load to a settling tank beyond the outfall. The appliances and methods should be such as to secure uniformity in discharge, in character of débris, and in rate of feed.

The apparatus for regulating discharge, described on pages 20 and 257, was one of the most satisfactory parts of the Berkeley equipment. Its most important feature, as affecting precision, was the delivery of the water through an aperture under a considerable head.

Uniformity of débris can hardly be secured without the employment of an artificial, narrowly limited grade, and the available means of sorting is the sieve. It is to be observed, however, that after a grade has been separated by sieves it is still subject to sorting by current, the current recognizing differences of form and density which the sieves ignore. When débris that has once been handled by the stream is to be used a second time, remixing may be advisable.

None of the devices we employed to feed débris to the current achieved uniformity. Those which depended on the flow of wet débris through an aperture failed because the proportion of water could not be kept constant. The others depended on handwork and experienced the irregularity usual to handwork. An apparatus planned near the end of the experimental work, but never tried, is of such promise that its essential features are here described.

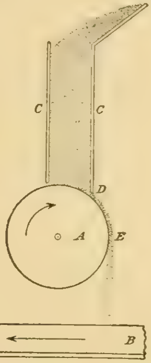

Figure 72.—Suggested apparatus for automatic feed of débris.

A drum, *A* in figure 72, is turned slowly by power, its rate being regulated by clockwork. Its position is above the trough containing the experiment stream, *B*. The surface of the drum is uniformly roughened. Above it is a vertical rectangular shaft, filled with moist débris. The shaft does not touch the drum. The width of the separating space at *D* is controlled by some suitable device. As the drum turns, a débris layer of uniform thickness is carried with it, and this falls into the stream. To prevent irregularities due to adhesion, a detaching device is placed at some point *E*, the device possibly consisting of an open-rank comb of elastic wire. The shaft should be smooth and of uniform section, so that the particles of débris near the drum may be brought into actual contact with one another by pressure of the débris above. That the débris may not be caused to flow by excess of moisture, it should be thoroughly drained before use. In a rough construction designed to test the practicability of the apparatus the drum surface was roughened by covering with a wire screen, and this was found to secure the delivery of the débris.

Uniformity of feed having been provided, the rhythms of transportation may be observed as oscillations in the débris delivered at the outfall. Rhymths of slope may be studied, at least initially, by observing changes in the profile of the water surface.

In the record of the Berkeley observations it is not practicable fully to discriminate rhythmic inequalities from those occasioned by irregularities of débris feeding, but there is reason to believe that several rhythms of different period coexist. The shortest rhythms are those connected with the dunes and antidunes, and these are evidently associated with rhythms of the flow of water.

RHYTHM IN THE FLOW OF WATER.

Reynolds,[1] treating of the flow of water through tubes, distinguishes two modes of flow as *direct* and *sinuous*. They are otherwise called steady and turbulent. In direct flow the filaments of current have simple lines, which are straight and parallel if the walls of the conduit are straight and parallel. In sinuous flow the filaments of current are neither simple nor parallel and may be intricately convoluted. The flow in tubes is direct for low velocities and sinuous for high, the critical velocity varying inversely with the diameter and the roughness of the tube and directly with the viscosity of the water. It would follow from his generalizations that the flow of such streams as were used in our experiments would be sinuous, and its actual sinuosity was a matter of observation. To a large extent the curvature of the flow lines was shown by the motions of minute suspended particles, and when this evidence was lacking it was still possible to infer diversity of current from continual changes in the configuration of the water surface.

It is probable that all the diversities of flow were rhythmic, for that is the nature of inequalities of motion developed by the interaction of constant forces; but in many cases the rhythms were so numerous and so related in period and other characters that their combination gave the impression of irregularity. In many other cases, however, some one rhythm was dominant, and these cases appear especially worthy of study.

The cycle of movements constituting a rhythm unit may be definitely related to space, or to time, or to both space and time. The pulsations of the water surface which obstructed our observations of water profile were manifestations of time factors. The regular sequence of dune crests was a manifestation of a space factor. The two phenomena coexisted. In the space interval from dune crest to dune crest certain elements of motion were constant. There was a large stationary vortex in the hollow between the crests (fig. 10, p. 31), and there might be stationary elements in the configuration of the water surface. At the same time the flow lines of the water at all points swayed in direction and were affected by variations of velocity, and these changes were rhythmic with respect to time. Doubtless many of the fluctuations belonged to or were associated with vortices which traveled with the general current. It is conceivable, or even probable, that the stationary features and the traveling features were coordinated, so that within the rhythmic space unit corresponding to the dune interval there was a cycle of variations of motion which was rhythmic with respect to time.

The rhythmic dunes marched slowly down the trough and with them marched the intercrest vortices and associated motions. To that extent the features of the bed controlled the features of the current. Nevertheless the dunes were not essential to the existence of a water rhythm characterized by a definite space interval. There was positive evidence that the dune interval was determined by a preexistent water rhythm. Not only was the dune interval a function of depth and velocity of current,[1] but the creation of dunes by water rhythm was repeatedly observed. In certain experiments a slow current, moving over a bed of débris artificially smoothed and leveled, was gradually quickened until transportation began. The movement of particles did not begin at the same time all along the bed but was initiated in a series of spots separated by uniform intervals, and the first result of the transportation was the creation of a system of dunes.

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[1] Reynolds, Osborne, An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous and of the law of resistance in parallel channels: Roy. Soc. Philos. Trans., London, vol. 174, pp. 935-982, 1883. Also, The two manners of motion of water: Roy. Inst. Great Britain Proc., 1884.

In certain experiments on flume traction a slow current, moving over a smooth channel bed of wood, swept along a small quantity of sand. With increase of the load of sand local deposits were induced, which took the form of thin straggling patches, similar to one another in outline and separated by approximately equal bare spaces. These moved slowly downstream, the mode of progress being similar to that of dunes, and with further increase of load they acquired the typical profile of dunes.

In both groups of experiments it was evident that the primary rhythm pertained to the water and was independent of the work of transportation. In the second group, where sand swept steadily forward over the whole area of the bed, it was evident that the water rhythm did not involve reversed currents along the bed and therefore did not include such stationary vortices as accompany dunes.

In the experiments on stream traction the development of dunes was conditioned by the three factors of velocity, depth, and load, besides an undetermined influence from fineness of débris.[2] It is probable that load and fineness enter only as factors of resistance, so that the essential conditions are velocity, depth, and bed resistance. Within certain rather wide ranges of value for these controlling factors the bed is molded into dunes. When the limit is exceeded by increase of velocity or resistance, or by decrease of depth, the dunes disappear and the bed becomes smooth and plane. At the same time the oscillations and other disturbances of the water surface are reduced; but as they do not altogether disappear it is to be inferred that the flow is still characterized by internal diversity.

With still further increase of velocity or resistance, or with further reduction of depth, another critical point is passed, and the process of traction becomes again rhythmic, but in an antithetic way. The bed is molded into antidunes, which travel upstream (pp. 31–34), and the water surface also is molded into waves, which copy the forms of the antidunes and move with them. The internal movement of the water is again characterized by a dominant rhythm, but the type of rhythm is different from that associated with dunes. The rhythm is also less stable, and its intensity exhibits a cycle of change. With low intensity the waves are nearly equal in height and length, but sooner or later inequalities develop and the higher waves overtake the lower and absorb them. This process increases the wave length in the upstream part of the trough, and the influence of the change is in some way communicated to the downstream end, where the waves are first formed, with the result that larger and larger waves develop. Finally a master wave, with curling crest, rushes through the trough from end to end, and this has the effect of wiping out the irregularities and restoring the status of low intensity. Various phases of the cycle are illustrated by the profiles in figure 12 (p. 33).

When combinations of velocity, resistance, and depth similar to those causing antidunes are made for a stream flowing through a rigid straight channel, without movable débris, the water develops surface waves, and these travel downstream faster than the current. They are initially rhythmic, but their period is unstable because their velocity of propagation varies with their size. A wave with slight advantage in size will overtake the one in front of it, and then the two will unite, making a wave with still higher velocity. Thus the system tends, for a time at least, toward reduction of the number of waves and increase of the wave interval. As the waves grow by composition, their fronts steepen and the culminating phase is that of a "roll wave," or bore.[1] It may be noted, in passing, that the pulsations frequently observed in the overfall of a dam are probably rhythms of this type.

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[1] Measurements of dune interval in the laboratory were too few to demonstrate the factors of control, but comparison of laboratory data with data from other sources leaves little question that control is exercised by depth, velocity, and fineness. In the laboratory, where depths were a matter of inches, the dune interval rarely exceeded 2 feet. In Mississippi River depths measured in scores of feet are associated with intervals measured in hundreds of feet. In tidal estuaries, where dunes of a special type are exposed at low tide, the depths of the formative currents are intermediate between those of the laboratory and those of the Mississippi, while the intervals are measured in feet or tens of feet. For data of the Mississippi see Johnson, J. B., Rept. Chief Eng. U. S. A., 1879, pp. 1963–1967, and Eng. News, 1885, pp. 68–71; Powless, W. H., Mississippi River Comm. Rept. for 1881, pp. 66–120; and especially Hider, Arthur, Mississippi River Comm. Rept. for 1882, pp. 83–88. For data on the dunes of tidal estuaries see Cornish, Vaughan, Geog. Jour., vol. 18, pp. 170–202, 1901. Hider finds that the dune interval is greater at high stages of the river than at low, the depth and velocity both decreasing with the change from high to low. Cornish's observations show that the interval varies directly with depth of current under conditions which make it probable that the velocity varies inversely with depth.

[2] Eger, Dix, and Seifert (Zeitschr. Bauwesen, vol. 56, pp. 325–328) found that under certain conditions dunes were developed in a sand of uniform grade but not in a finer sand composed of several grades. In our experiments the smooth phase of transportation had greater range with mixed grades than with single grades.

It may be assumed, at least tentatively, that all the dominant rhythms observed in straight conduits are initiated at the intake. Those associated with low velocity and an immobile bed appear to be stationary, but with a mobile bed they develop dunes, and they then travel downstream with the dunes. Those associated with high velocity and an immobile bed develop waves of translation which travel downstream. With a mobile bed antidunes are developed, and surface waves travel with them upstream. It is possible that the antidune waves coexist with the waves of translation, and that the cycle of intensity in the antidune phenomena results from the interactions of the two systems.

If there is warrant for the various correlations above indicated, the phenomena developed by our experiments in connection with modes of débris transportation afford a basis of classification for a considerable body of water rhythms. What we have called the smooth phase of traction marks a critical phase of water flow separating two types which are characterized by dominant rhythms, and the two dominant rhythms are in some way antithetic. The nature of their antithesis is not known to me, nor is the character of either rhythm; but it appears that the experimental and analytic study of the rhythms constitutes a field of research which is at the same time promising and important. I assume that the definite rhythms of water by which, when débris is present, the dunes and antidunes are caused are susceptible of analytic treatment, and I believe that the experiment trough affords the means of preliminary delineation and ultimate verification.

THE VERTICAL VELOCITY CURVE.

No systematic study was made of the distribution of velocities within the streams of the laboratory, but incidentally, in connection with several different minor inquiries, the vertical distribution of velocities in the medial plane was recorded; and it happens that some of these records serve to illustrate the dependence of that distribution—the vertical velocity curve—on certain conditions. The observations were made with the Pitot-Darcy gage.

The first to be reported were made in connection with a comparison of the free outfall (fig. 1, p. 19) and the contracted outfall (fig. 3, p. 25). The trough used with free outfall had smooth sides and bed, was 1 foot wide, and was set level. The stream of water, 0.734 ft.³/sec., carried no débris. Its surface slope gradually increased toward the outfall, and the mean velocity increased with the fall of the surface. Velocities were measured at three points, respectively, 5.5 feet, 2.3 feet, and 0.8 foot from the outfall. Their curves, given in figure 73, show that the acceleration as well as the velocity increased as the outfall was approached, and that there was a coordinate modification of the shape of the curve. In the first curve it is evident, despite a discordance among the determined points, that the level of maximum velocity is somewhat above mid-depth; in the second the maximum is near mid-depth; and in the third it is below. The acceleration, for which an integrated expression appears in the horizontal space between curves,

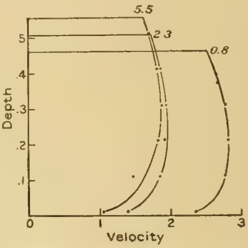

FIGURE 73.—Modification of vertical velocity curve by approach to outfall.

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[1] See Cornish, Vaughan, Progressive waves in rivers: Geog. Jour. (London), vol. 29, pp. 23–31, 1907.

seems to have affected the lower part of the current more than the upper.

The trough used with contracted outfall was 0.92 foot wide and was contracted, in the manner shown in figure 3 (p. 25) to 0.30 foot. The oblique walls producing the contraction were 3 feet long. The first velocity station was 1.5 feet from the outfall, at a point where the width was 0.64 foot; the second and third were at 0.75 and 0.25 foot from the outfall, corresponding to widths of 0.47 and 0.35 foot. The velocity curves, given in figure 74, show the descent of the plane of maximum velocity from a position slightly above middepth to near the bottom. The acceleration, in this case connected with contraction of channel, as well as with the release at outfall from the channel resistance, is a function of depth.

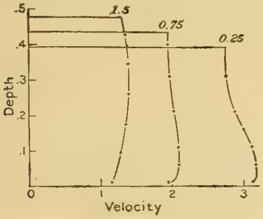

FIGURE 74.—Modification of vertical velocity curve by approach to contracted outfall.

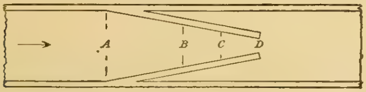

FIGURE 75.—Plan of experiment trough with local contraction. The letters show stations at which velocities were observed, and are repeated in figures 76 and 77. Scale, 1 inch=2 feet.

In the third arrangement a trough 0.92 foot wide, with a slope of 0.58 per cent, was contracted at one point in the manner indicated in figure 75. This gave to the stream such a profile as is sketched in figure 76. Velocities were measured at four points, the distances from the point of extreme contraction being 2.0 feet, 1.0 foot, 0.5 foot, and 0, and the corresponding widths of current 0.92, 0.55, 0.37, and 0.19 foot. The velocity curves are plotted in figure 77. The level of maximum velocity is at or near the surface at the point of initial contraction, *A*, and then drops quickly, being below 0.9 depth in the narrowest strait, *D*. In this case also the acceleration appears to increase in regular manner with distance from the surface.

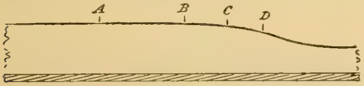

FIGURE 76.—Profile of water surface in trough shown in figure 75. Scale 1 inch=2 feet.

To avoid the peculiarities observed near the outfall, as well as those appropriate to intake conditions, all other determinations of the curve were made near midlength of the trough, the ordinary distance from the outfall being 17 feet and the least distance 13 feet.

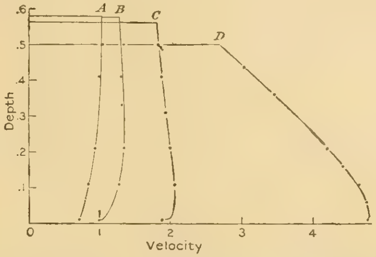

FIGURE 77.—Modification of vertical velocity curve by local contraction of channel. The letters indicate positions of velocity stations in trough. (See fig. 75.)

In figure 78 are three curves illustrating the influence of slope of channel. The trough was 1.96 feet wide and its sides and bed were smooth; the discharge was 1.119 ft.^{3}/sec. Curve *A* shows velocities 17 feet from the outfall, with the trough level; *B* corresponds to a slope of 0.26 per cent and *C* to 0.56 per cent. With the trough level, maximum velocity occurs at about 0.75 depth, and with both inclinations of trough its position is indicated at from 0.2 depth to 0.3 depth. As curve *C* differs in type from all others obtained, and as it may be made harmonious by rejecting a single observation, it is thought probable that the dotted line better expresses the fact. Its

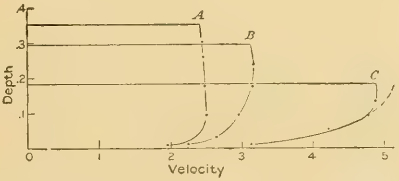

FIGURE 78.—Modification of vertical velocity curve when mean velocity is increased by change of slope.

substitution throws the maximum to the surface of the water and makes a consistent series of the three curves.

In another series of observations the trough remained horizontal while the discharge was varied. The width was 0.66 foot, and the discharges 0.182, 0.363, 0.545, 0.734, and 0.923 ft.^{3}/sec. The resulting curves (fig. 79), with exception of that for the smallest discharge, form a consistent series, the level of maximum velocity rising slowly with increase of discharge. In this case also the discordant curve may be brought into harmony by the rejection of a single observation, and a substitute curve is suggested in the diagram by a broken line.[1]

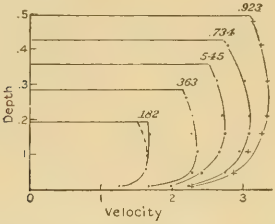

FIGURE 79.—Modification of vertical velocity curve when mean velocity is increased by change of discharge. The corresponding discharges are indicated in ft.^{3}/sec.

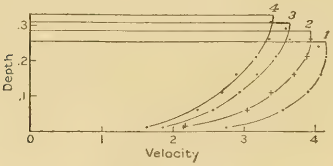

FIGURE 80.—Modification of vertical velocity curve by changes in the roughness of the channel bed. Curve 1, paraffin; 2, roughness of débris grade (A); 3, roughness of grade (D); 4, roughness of grade (F).

In another series the texture of the channel bed was made to vary. Constant features were the discharge, 0.734 ft.^{3}/sec.; the width, 0.92 foot; the slope, 0.58 per cent; and the texture of the channel sides, which were planed and unpainted. The varieties of bed texture were (1) paraffin, coating a smooth board; (2) a pavement of débris of grade (A); and (3 and 4) similar pavements with grades (D) and (F). The observed curves, given in figure 80, indicate that the resistance occasioned by a rough bed retards the whole current but retards the lower parts in greater degree than the upper, so that the level of maximum velocity is raised. The amount of retardation is greater as the texture of the bed is coarser.

In figure 81 are two curves illustrating the influence of load on the vertical distribution of velocity. One curve was observed in a stream without load, flowing over a smooth and horizontal bed, the other in the same stream when carrying a load of 17 gm./sec. on a self-adjusted slope of 0.64 per cent. To judge from the data shown in figure 78 (p. 245), the effect of slope alone would be to double or nearly double the mean velocity, but the actual increase was only 13 per cent. The acceleration due to slope was almost wholly neutralized by the retardation due to roughness of bed and to the work of traction. The retardation had also the effect of raising the level of maximum velocity.

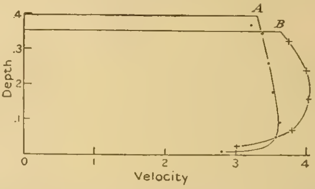

FIGURE 81.—Modification of vertical velocity curve by addition of load to stream, with corresponding increase of slope. *A*, without load; *B* with load.

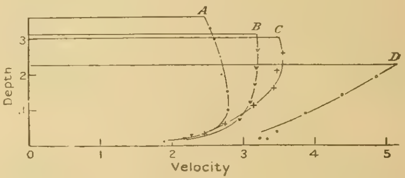

FIGURE 82.—Modification of vertical velocity curve by addition and progressive increase of load.

Similar contrasts are shown in figure 82, where the curve for an unloaded stream is compared with curves for the same stream when transporting three different loads. The constant factors in this case are: Width of channel,

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[1] In this instance, in the one before mentioned, and also in the case of three curves in figure 80 the aberrant point records a measurement which was made very near the surface of the water. In such positions the constant of the Pitot-Darcy gage has a special value, and it is on the whole probable that the apparent errors of observation are occasioned by an error of the rating formula. The matter is discussed in Appendix A.

0.66 foot; discharge, 0.545 ft.³/sec.; grade of débris, (C). The variables are as follows:

Load..........gm./sec..	0	38	53	194
Slope of bed...per cent..	0	0.38	0.56	1.14
Depth at 17 feet from outfall..............feet..	0.353	0.313	0.303	0.226
Mean velocity...ft./sec..	2.57	2.64	2.73	3.66
Level of maximum velocity; measured from the surface as a fraction of depth................	0.7	0.3	0	0
Letter indicating curve in figure 82..............	*A*	*B*	*C*	*D*

With the slope of 0.38 per cent the sand moved in dunes; with 0.56 per cent the phase of traction was transitional between the dune and the smooth; with 1.14 it was transitional between the smooth and the antidune. The conspicuous change associated with the addition of load is the raising of the level of maximum velocity, and this is correlated also with increase of slope, increase of mean velocity, decrease of depth, and modification of the mode of traction.

The plotted points for velocities near the channel bed are irregular when the observations were made above a bed of loose débris, and little use has been made of them in drawing the curves. As previously mentioned, the presence of the gage caused a deflection of the lines of flow and the formation of a hollow in the bed. Not only was it impossible to observe with accuracy the relation of the instrument to the normal position of the bed, but the velocity observed was higher than that normally associated with the depth at which the instrument was placed. (See Appendix A.)

In most of the groups of curves the variations of form are associated with simultaneous variations of so many conditions that the nature of the control is not evident. For satisfactory interpretation a fuller series of observations seems to be required, but certain inferences may be drawn from those before us.

Many of the peculiarities of form are connected with the position of the level of maximum velocity. The movements of the maximum in relation to depth of current are of two kinds. It rises with increase of depth when that increase is caused by increase of discharge (fig. 79). It falls with increase of depth when that increase is independent of discharge (figs. 78, 81, and 82). Apparently depth, considered by itself, is not a factor of control. The maximum rises with increase of mean velocity when that increase is due to increase of discharge (fig. 79), or of slope (fig. 78), but falls with increase of mean velocity when the increase is due to lessened resistance of the channel bed (figs. 73, 80, 81, and 82). Apparently mean velocity, considered by itself, is not a factor of control. If we give attention to the three factors on which depth and mean velocity chiefly depend—namely, discharge, slope, and bed resistance—a more consistent relation is found. Variations of discharge affect only the group of curves in figure 79, and there the maximum rises with increase of discharge. Slope affects the groups in figures 78, 81, and 82, and in each case the maximum rises with increase of slope. Bed resistance affects the groups in figures 80, 81, and 82, and in each case the maximum rises with increase of resistance.

The lowering of the level of maximum velocity as the point of outfall is approached (fig. 73) is a harmonious feature, but in that case there is substituted for progressive reduction of bed resistance an abrupt cessation of all channel resistance. The resulting acceleration is propagated upstream, and its amount has a vertical distribution connected with pressure. In the case of contracted outfall (fig. 74), there is added an effect of convergence, which still further illustrates the graduation of acceleration in relation to pressure. The influence of contraction is important in other connections, but need not be further discussed in this place.

The influence of outfall may extend to a considerable number of the curves here figured. In most of the experiments made without contraction at outfall there was progressive decrease of depth and increase of mean velocity, from some point near the head of the trough to its end. This was most marked when the bed of the trough was horizontal (figs. 73, 78*A*, 79, 81*A*, and 82*A*). Reasoning from the observed fact that acceleration increases with depth, I think it probable that under such conditions the level of maximum velocity lies lower than it would with a uniform mean velocity.

Returning to the consideration of discharge, slope, and resistance, we may note that the variable resistance with which variations of the curve have been definitely correlated is bed resistance. In all the experiments the channel sides had the same texture, so that the side resistance was approximately proportional to the depth. The level of maximum velocity thus has the same relation to side resistance as to depth; it sometimes rises and sometimes falls when side resistance is increased. While a probability exists that side resistance influences the position of the maximum, the nature of its influence is not shown by the observations under consideration.

Discharge and slope, or the energy factors which they help to measure, urge the water forward, and their influence is applied to the whole stream. Bed resistance holds the stream back but is applied to its base only. The *obvious* tendency of these forces is to make the upper part of the stream move faster than the lower and produce a velocity curve with maximum at the water surface. This tendency is opposed by some other factor, unknown, which tends to depress the level of the maximum. Whatever that other factor may be, it loses in relative importance when discharge, slope, or bed resistance is increased.

A noteworthy feature of the curves is a tendency to change in character near the bed. The observations are not so precise nor so full as to afford a distinct characterization of the change, but there can be little question of its existence. It would appear that the peculiar conditions near the bed give great local importance to some factor of velocity control which is elsewhere of minor importance. Attention may also be directed to the fact that none of the curves resembles an ordinary parabola with horizontal axis. Had these been the vertical velocity curves to which mathematical formulas were first fitted, the equation of the parabola would not have been used.

The statement, above, that the factor tending to depress the level of maximum velocity below the water surface is unknown is perhaps rash, for several theories as to its nature have been advanced with confidence. To put the matter more cautiously—it has seemed to me that each theory of which I have read was effectually disposed of by the discussion which it aroused. However that may be, there is certainly room for another suggestion, and this I proceed to offer.

Reynolds[1] arranged an experiment in which a liquid was made to flow over another denser liquid, the two being immiscible. Below a certain velocity the surface of contact was smooth, but above the critical velocity the surface was occupied by a system of equal waves, which moved in the direction of flow but more slowly. With miscible liquids, or with two bodies of identical liquid, the waves are replaced by vortices. Under some conditions the vortices are as regularly spaced as the waves, but usually they are less regular, and various complications arise. The development of such vortices may readily be watched on a river surface wherever adjacent parts move with quite different velocities or move in opposite directions. Such vortices have vertical axes, and their direction of rotation is determined by the differential motion of the adjacent currents. If we conceive the water of a vortex as a body between parallel and opposed currents, then its direction of rotation is due to a mechanical couple contributed by the currents.

Transferring attention to the longitudinal vertical section of a stream, we find a couple of which one element is the general forward movement of the current and the other is the bed resistance. These tend to produce and maintain vortices with horizontal axes transverse to the channel and with forward rotation—that is, with the rotation of a wheel rolling forward in the direction of flow. To visualize these features, figure 83 gives an ideal section of a stream, with flow from left to right, and the ovals *A*, *B*, *C* represent a system of forward-rolling vortices. The arrows within an oval show direction of rotation, and it is important to recognize that the motions they indicate are referred to the center of the vortex, or to the vortex as a whole, and not to the fixed bed of the channel. With reference to the bed all parts of the vortex are moving toward the right, the lower part merely moving slower than the upper.

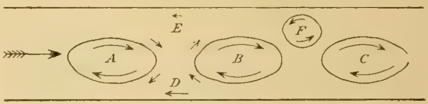

FIGURE 83.—Ideal longitudinal section of a stream, illustrating hypothesis to account for the subsurface position of the level of maximum velocity.

The tendency of vortices toward circular forms leaves certain tracts of the section unoccupied by the system of vortices. Consider the tract *D*, bounded below by the bed and above by parts of vortices *A* and *B*, and give attention to the motions by which the water in the tract is surrounded and influenced, taking care to refer each motion to the middle of the tract itself. Thus referred, the motion of the adjacent part of the rear vortex *A* is to the left and downward, that of the forward vortex *B* is to the left and upward, and that of the bed is to the left. The motions are indicated by arrows. The influences of the vortices tend to make the water about *D* rotate backward, while the influence of the bed tends to make it rotate forward. The result is not a priori evident, but may be assumed to be something different from simple rotation. Its possibilities will again be referred to.

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[1] Roy. Soc. London Philos. Trans., vol. 174, pp. 943-944, 1883.

Now consider the tract *E*, bounded below by parts of *A* and *B* and above by the water surface, and give attention to the motions by which its water is affected. Motions being referred as before to the tract itself, that of vortex *A* is to the right and downward, and that of vortex *B* is to the right and upward. Above is the motion of the air, which, in the absence of wind, is to the left, as indicated by an arrow. The three influences to which the tract of water is subject all tend to give a backward rotation, as indicated in a similar position at *F*. The vortex *F* is secondary to the *A*, *B*, *C* system and rotates in the opposite direction. If its motions be referred to the fixed stream bed, it is evident that the water in its upper part moves in the direction of the current less rapidly than the water in its lower part. The existence of such a vortex therefore tends to reduce the average velocity at the surface of the current and increase it at some lower level.

Abandoning now the specific and ideal case, we may state the hypothesis in general terms. Among the important causes of vortical motion in a river or other stream is the mechanical couple occasioned by the general forward motion of the water in conjunction with the resistance of the bed. This tends to form vortices with horizontal axes and forward roll; and the tendency is probably strongest in the lower part of the stream. In a space adjacent to two forward-rolling vortices there exists a tendency toward the development of a secondary, backward-rolling vortex, but this tendency is apt to be nullified by other and adverse influences except in the upper part of the stream. The free surface of the water does not oppose the development of such reversed vortices. Wherever reversed vortices abound the velocity at the surface (averaged with respect to time) is less than at some level below the surface.

The hypothesis as stated has no stationary element, but the phenomena of incipient dunes show that in certain cases repetitive motions are associated with stationary space divisions. A supplementary suggestion assigns these repetitive motions, or their initial phases, to the triangular space *D* in the ideal diagram, figure 83. The forces tending toward rotation in that space are antagonistic; and the suggestion is (1) that they produce some sort of alternating movement with regular periodicity, and (2) that the time interval of this movement, in combination with the forward movement of the major vortices *A*, *B*, *C*, yields a stationary space interval.

An investigation based on this line of suggestion and designed to test it should lead also to an explanation of the observed changes in the method by which traction is accomplished. The dune method is associated with a depth which is large in relation to the mean velocity and with a moderate bed resistance. It is replaced by other methods in consequence of (1) a reduction of depth, or (2) an increase of velocity, or (3) an increase of resistance. Reduction of depth diminishes the space for development of the hypothetic vortices. Increase of velocity or of resistance tends to enlarge their pattern. In either case the coercion of the water surface restricts the freedom of vortical movements and imposes conditions tending to modify their system.

THE MOVING FIELD.

The competent investigator is resourceful in the creation of new apparatus and methods as the need for them arises. While fully conscious of this fact, and of the further fact that no device is of assured value till it has been tried, I yet can not forbear to mention, for the benefit of others, a method which the Berkeley experience leads me to think valuable for the study of the internal details of a current of water.

In a current limited by the sides of a narrow, straight trough transverse movements are largely suppressed, so that most of the action can be learned from observation of what takes place in vertical planes parallel to the axis. The movements in a vertical plane may be exhibited by giving to the trough a glass side and by giving to the water in that plane exclusive illumination. When one of our laboratory currents, being illuminated from above, was viewed from the side, small particles in suspension were seen to be conspicuous, so conspicuous, in fact, as to resemble the motes in a sunbeam. Some of the particles were shreds of wood fiber worn from the trough, and these could be more easily followed by the eye because of their distinctive forms. Impressed by this phenomenon, I am confident that water movements in a vertical plane can be effectively revealed by giving to the water a suitable amount of suitable suspended material and by giving to the selected plane a brilliant and exclusive illumination.

With the aid of such simple arrangements much may be seen, but measurement will be difficult; and vortical movements may not be easily discriminated from those which are merely sinuous. It is believed, however, that both these results may be achieved by aid of the moving field. In a very simple form this device was employed by us in the study of processes of traction (p. 27), and despite the crudity of the apparatus it was found to be highly efficient. An experiment trough having in its side a glass panel, *AA* in figure 4, bore a sliding screen, *B*, in which was an opening, *C*. Moving débris was watched through the opening at the same time that the screen and opening were moved in the direction of the current. To the field of view was thus given a horizontal motion, and that motion was, in effect, subtracted from the motions of the objects observed. The apparent motions were motions in relation to the moving field, and not to the fixed trough. No provision was made for determining the velocity of the field, nor for measuring the apparent motions of the objects viewed; but even without these devices for quantitative work, the possibilities of the method of observation were sufficiently evident. With the necessary supplementary devices, the moving field promises to measure the horizontal and vertical components of motion in any part of the vertical section, and it thus makes possible the complete delineation of velocities and directions of details of current, so far as those details may be exhibited in longitudinal vertical sections. By giving to the field a suitable velocity it should be possible to see a traveling vortex which rotates in a vertical plane, just as vortices of horizontal rotation are seen on the surface of a stream.

A notable defect in the Berkeley arrangement was the requirement that the observer move his head in unison with the moving field. This interfered with steadiness and also limited narrowly the space covered by an observation. It could be remedied by substituting for the slide a car which should carry both observer and peephole at a determined rate.

Another suggested arrangement places the eye of the observer at a fixed telescope and moves the field by means of a rotating mirror. This is illustrated by figure 84, where the trough *T* is shown in plan. The telescope *E* views the trough through the mirror, which is pivoted on a vertical axis at *M*. As the plane of the mirror rotates from *a* to *b* the field commanded by the telescope moves from *A* to *B*. It is evident that if the angular velocity of the mirror is constant the linear motion of the field along the trough will be relatively fast at *A* and *B* and relatively slow at *C*. The error thus arising may be avoided by some device of the nature of linkage. It will be corrected with sufficient approximation if the axis of the mirror be controlled by a rigidly attached arm *MD*, which is in turn controlled by an arm about one-third as long, the two having sliding contact at *D* and the short arm revolving uniformly about a vertical axis at *F*.

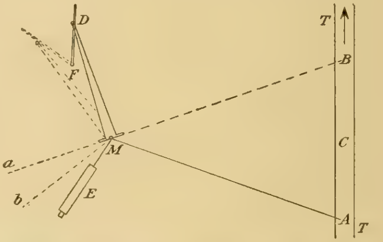

FIGURE 84. Diagrammatic plan of suggested moving-field apparatus.

APPENDIX A.—THE PITOT-DARCY GAGE.

SCOPE OF APPENDIX.

Many measurements of velocity were made with the Pitot-Darcy gage, but as only a few have been finally utilized in the preparation of the report, a discussion of the instrument seemed not appropriate to the main text. Certain phases of our experience, however, are thought worthy of record because they have practical bearing on the utility and the use of such gages, and these are the subject of the appendix.

FORM OF INSTRUMENT.

Darcy developed the Pitot tube by adding a second tube, differently related to the current, and by connecting the two above with a chamber from which the air was partly exhausted. The water columns in the two tubes were thus lifted from the vicinity of the water surface to a convenient position, where their difference in height could readily be measured. In the gages constructed for our use the aperture of one tube was directed upstream and that of the other downstream. The tubes were borings in a single piece of brass, which was shaped on the outside in smooth contours, designed to interfere the least possible with the movement of the water. The form first given was afterward modified, and figure 85 shows the third and last design, with which most of the work was done. The openings had a diameter of 0.1 inch. At the opposite or upper end of the brass piece were stopcocks, and above these connection was made with rubber tubes, which led to the complementary part of the apparatus, where the difference in height of the two water columns was observed. It is convenient to call the member exposed to the current the *receiver*, and the complementary member the *comparator*.

In the comparator were two glass tubes, straight and parallel, with internal diameters of about 0.8 inch. At the top they were connected by an arch, and at the summit of the arch was a branch tube, with a pet cock, used in regulating the amounts of air and water. At the bottom they communicated with the rubber tubes through a brass piece, in which were two stopcocks, connected by gearing so as to open and close together. These parts were mounted on a board which also carried a scale of inches and decimals. A sliding index was arranged so that it could be set by the meniscus of a water column and its position then read on the scale; and there was a fixed mirror behind the tubes to aid in avoiding error from parallax. The board was supported in an inclined position, the slope given to the tubes and scale being that of 2½ horizontal to 1 vertical. This had the effect of making the movements of the columns 2.69 times as great for the same change of pressure as they would be if the tubes were vertical.

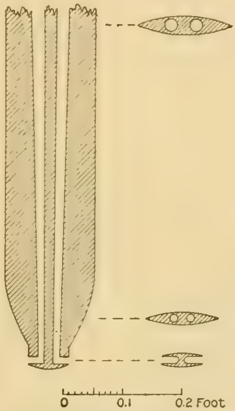

FIGURE 85.—Longitudinal section of lower end of receiver of Pitot-Darcy gage No. 3, with transverse sections at three points.

In preparing for observation, the internal air pressure was so adjusted that the columns stood near the middle of the scale. The receiver was then held, by a suitable frame, in the selected part of the current, and the stopcocks were opened. In the glass tube connected with the receiver opening facing upstream the column rose; in the other tube it fell. When the full effect of the current had been realized, the stopcocks at the bottom of the comparator were closed, and the heights of the columns were then read.

The use of the gage to measure velocities close to the bed of débris proved impracticable because the presence of the receiver modified the movement of the water and thereby modified the shape of the bed. (See pp. 26, 155.) This effect could have been reduced by using a different form of receiver. Darcy and Bazin[1] bent the tubes at the bottom in such a way that one or both openings met the water at some distance upstream from the vertical part of the tubes, and it is probable that the adoption of their design would have diminished the difficulty, although it could not have removed it. With such a design, however, the practicable forms for the second opening relate it to the piezometer, and the advantage of the downstream opening is lost.

That part of the design of the comparator which consists in the inclination of tubes and scale is not to be recommended. It refines by magnifying the reading, but it introduces possibilities of error in other ways. If the tubes are not straight or are not equally inclined, an error is occasioned which does not enter if they and the scale are vertical. Evidence of such error was found in the fact that the still-water or zero-velocity readings of the two columns were not always identical, but no ready means of correction was discovered.

Another source of error was detected in inequalities of sectional area of the glass tubes of the comparator. To show the nature of this error, let us assume that the pressure of the current at the upstream opening of the receiver is exactly equal to the negative pressure, or suction, at the downstream opening. If the glass tubes are of uniform and equal bore, one column moves upward just as much as the other moves downward, and the volume of air above the columns is unchanged. Now, assume that the tube containing the rising column has the greater diameter. It is evident that equal movement of the two columns will displace more air in the one tube than it will provide space for in the other, and the pressure of the confined air will be thereby increased. The effect of the increased pressure will be to lower both columns. There is also a secondary effect of small amount connected with the fact that the pressure of the confined air plus the head of water between the tops of the columns and the surface of the stream, on the one hand, and the atmospheric pressure, on the other, are in equilibrium, but into this we need not here enter.

As a means for the discussion of these errors the tubes were calibrated, by Prof. J. N. Le Conte, in the following manner: The tubes being closed at the bottom, a weighed quantity of water was introduced into one and the height of its column was read. By repeated additions of water and repeated readings the volumes of divisions of each tube were thus measured, the divisions being approximately 1.5 inches in length. In similar manner the volume was measured of the space above the straight tubes to the pet cock. The average sectional area of one tube was found to be 2.5 per cent greater than that of the other. The sectional area in the larger tube was found to vary through a range of at least 2.6 per cent, and the range for the smaller tube was 4.5 per cent.

A table of corrections to readings was computed from the data of calibration, and this table was practically applied. In comparing the rise of one column with the associated fall of the other the greatest correction applied amounted to a little less than 1 per cent. In the determination of velocity the largest correction applicable for this reason was about 0.3 per cent. These corrections, however, pertain only to the discussions of the instrument in the following pages. In the ordinary work of the gage they were not applied, because it was found that the errors of this class were practically eliminated when the same methods were employed in the preparation and in the use of rating formulas. The matter is mentioned here chiefly because errors from unequal tube caliber, which may sometimes prove important, appear not to have been allowed for in the discussions of Pitot-Darcy gages.

RATING METHODS.

The first and second gages were rated by the method of floats; the third was twice rated by the running-water method and several times by the still-water method. The floats used were vertical cylinders of wood so adjusted that the submerged depth was twice the distance below the water surface of the apertures of the receiver. Some of the still-water ratings were made at the Geological Survey's rating station at Los Angeles, where a car running on a track at the side of a reservoir drew the receiver through the water of the reservoir. The others were made later in the long trough of the Berkeley laboratory, the car in this case running above the water. In the application of the running-water method a measured discharge was passed through a rectangular trough and a survey of velocities throughout a cross section was made by means of the gage. By using in this survey the rating formula obtained by the still-water method, and then comparing the mean velocity thus computed with that computed from the discharge and sectional area, a correction is obtained which may be applied to the still-water rating formula. Only a single comparison of this sort is practically available in connection with our instruments, and the terms of this are:

---

[1] Bazin, F. A., Recherches expérimentales sur l'écoulement de l'eau dans les canaux découverts: Acad. sci. Paris Mém. math. et phys., vol. 19, p. 49, Pl. IV, 1865. This memoir was published also as part of "Recherches hydrauliques," by H. Darcy and F. A. Bazin.

	Ft./sec.
Mean velocity by discharge and area	1.98
Mean velocity by gage (with still-water rating)	2.08±0.07

The resulting correction to the still-water ratings is −5 per cent, but this determination has small value because of the large probable error of one of the compared determinations.

The fact that the apparent correction is small is in accord with a property of the gage independently observed. By reason of the sinuosity of flow lines in a stream, the directions of motion are not parallel to the axis of a straight channel. Therefore, a current meter which records the velocity in the direction of flow instead of the component of velocity parallel to the channel axis yields an overestimate of mean velocity. Some Pitot-Darcy gages have been found to overestimate velocity when placed obliquely to the direction of flow, and for such the correction would be large. It was found, however, that the Berkeley gage when placed somewhat obliquely to the current gave a lower reading than when facing it squarely, and through this property it tended automatically to correct its readings for obliquity of current. If the correction were perfect, the still-water rating and running-water rating should be the same.

RATING FORMULA.

In the still-water ratings velocities independently determined were compared with resulting changes in the water columns of the comparator. Starting from the same level, one column rose with increase of speed and the other fell. Except for the influence of modifying conditions the changes should be equal, the positive velocity head being of the same amount as the negative velocity head. To test this point various sets of observations were plotted on section paper, the readings of the rising column being taken as abscissas and the readings of the falling column as ordinates. In most cases the plotted points fell well into line, and there was no question that the line represented by them was straight. That is, the true ratio of the negative pressure at the downstream opening of the receiver to the positive pressure at the upstream opening was constant, under the conditions of this particular series of trials. The value of the ratio was found to vary with conditions, and the several values found are so near unity as to confirm the theoretic belief that unity is the normal value.

In considering the variations of value it is first to be noted that the gage with which the observations were made, No. 3, being symmetric, could have either opening turned upstream, and it was in fact used both ways, with record of its position. But its symmetry was only approximate and therefore the two positions gave different results. Used in one way it will be called No. 3a, and in the other way No. 3b. It also happened that between the date of the Los Angeles ratings and that of the Berkeley ratings the receiver was accidently marred at one of its openings, and though its form was afterward restored as nearly as possible, some difference remained which affected its constants. The values of the pressure ratio are accordingly arranged in four groups in Table 81. Two of these groups also are subdivided with reference to the position of the receiver in relation to the perimeter of the current.

The ratio was notably larger after the accident than before, and the change was greater for 3a than for 3b. The greatest value of the ratio was given by trials in which the receiver ran close to the side of the reservoir, which in that case was a plank trough. The interpretation of these results will be considered in another connection.

TABLE 81.—*Ratio of the suction at one opening of the Pitot-Darcy gage to the pressure at the other.*

Place of rating.	Conditions.	Ratio, suction to pressure.	
		Gage 3a.	Gage 3b.
Los Angeles....	Deep water......	0.993±0.015	1.005±0.005
Berkeley........	Shallow, mid-depth... ...	1.038± .007	1.010± .002
Do..........	Shallow, near bed....	....	1.016± .003
Do.........	Shallow, near surface... ..	....	1.014± .005
Do..........	Shallow, near side...... ..	1.052± .004	....

Let h represent the vertical space through which the column of water is raised by pressure from velocity V on the upstream opening of the receiver, and h_1 the simultaneous depression of the column connected with the downstream opening. Then, each being assumed to equal the velocity head,

$$h = h_1 = \frac{V^2}{2g} \quad \text{(116)}$$

$$h + h_1 = \frac{2}{2g} V^2 \quad \text{(117)}$$

In practice the full velocity head is not realized in instruments of the Pitot-Darcy type, and the coefficient determined by rating is less than $\frac{2}{2g}$. It is a common experience also in practical application of hydraulic formulas to find that qualification is advisable in other respects. I therefore substituted tentatively for (117) the formula

$$h + h_1 = kV^u \quad \text{(118)}$$

and sought empiric values of u and k. The readings of the comparator corresponding to h and h_1 may be called H and H_1. The zero of the comparator scale being at its lower end, the difference between the readings corresponds to the sum of the spaces h and h_1. The readings are in inches, while the unit used for h, h_1, and g is the foot. Moreover, from the inclination of the comparator, the space between the two columns, as read on the scale, is 2.69 times the vertical space $h+h_1$. Therefore, the product of 12 by 2.69 being 32.28,

$$H - H_1 = 32.28\,(h + h_1) \quad \text{(119)}$$

Substituting in (118), we have

$$H - H_1 = 32.28\,kV^u \quad \text{(120)}$$

or, making $K = 32.38\,k$,

$$H - H_1 = KV^u \quad \text{(121)}$$

The observed quantities being H, H_1, and V, it was possible to plot on logarithmic section paper any series of values of $H-H_1$ in relation to the associated values of V, and thus compute graphically the corresponding values of u and K. The values were computed for all series of observations represented in Table 81, and they are given in Table 82. The mean of the seven values of u is 2.00, but their range is notable. The deviations from the normal may be ascribed in part to accidental errors. In the case of the third value, 1.90, and of the seventh, 1.94, the plotted positions are so scattered as to admit of considerable latitude in the drawing of the equation lines, but the control is much stronger for the values 2.09 and 2.12, and these could not be greatly reduced without violence to the facts of observation. It seems clear that the exponent is not wholly free from the influence of special conditions.

TABLE 82.—*Values of K and u in $H-H_1=KV^u$.*

Place of rating.	Conditions.	Gage.	K	u
Los Angeles........	Deep water..............	3a	0.70	2.00
Do.	....do......	3b	.62	1.98
Berkeley............	Shallow, mid-depth.....	3a	.72	1.90
Do..............	.....do.........	3b	.52	2.09
Do..............	Shallow, near bed.	3b	.70	1.91
Do..............	Shallow, hear surface...	3b	.46	2.12
Do..............	Shallow, near side.......	3a	.66	1.94

For the practical purpose of rating the instrument, however, there is no advantage in departing from the normal exponent, and that was employed in the preparation of rating tables. The formula used for inferring velocities from readings is

$$V = A\sqrt{H - H_1} \quad \text{(122)}$$

in which

$$A = \frac{1}{\sqrt{K}} = \frac{1}{\sqrt{32.28k}}$$

The values of A, graphically computed, are given in Table 83, and these values were used in the computations of velocities.

TABLE 83.—*Values of A in $V=A\sqrt{H-H_1}$ and values of gage efficiency.*

Place of rating.	Conditions.	Values of A		Efficiency of gage.	
		Gage 3a.	Gage 3b.	3a.	3b.
Los Angeles	Deep water	1.22±0.02	1.26±0.01	0.67	0.63
Berkeley	Shallow, mid-depth	1.29± .04	1.30± .02	.60	.59
Do	Shallow, near bed	......	1.24± .01	.....	.65
Do	Shallow, near surface	......	1.37± .03	......	.53
Do	Shallow, near side	1.26± .03	....	.63	..

An inspection of the values of A with due attention to their probable errors serves to show that their differences are not to be regarded as wholly accidental, but must be ascribed in part to the variation of the instrumental constant with conditions. That the nature of the variations may be appreciated, the conditions will be more fully described. As already stated, gages 3a and 3b are the same symmetric instrument, but with opposite faces turned toward the current, while the instrument was modified to some minute extent by an injury and repair occurring between the Los Angeles and Berkeley ratings. Practically there were four gages, but so far as the mechanician could make them the four gages were identical in form. The reservoir at the Los Angeles rating station was broad and deep. The course followed by the receiver of the gage was several feet from the bank, at least 6 inches below the surface, and at least 1 foot above the bottom. The plank reservoir used in Berkeley was 1.96 feet wide, and the depth of water was 0.44 foot. In the ratings tabulated as at "mid-depth" the opening of the receiver was central in the cross section of the water. In the "near bottom" rating the center of the opening (its diameter being 0.01 foot) was 0.02 foot from the bottom; in the "near surface" rating the center was 0.03 foot below the surface of the water; and in the "near side" rating the center was 0.25 foot above the bottom and varied from 0.01 to 0.11 foot in its distance from the side, the course and the trough side not being quite parallel. The several relations of the opening to the water section are shown in figure 86.

There is nothing novel in the variation of the instrumental constant with minute differences in the shape of the receiver. This has been observed by all critical users of such instruments, and the custom is well established of giving a separate rating to each receiver. So far as I am aware the variation of the constant with the relation of the receiver to the walls of the conduit and to the water surface has not previously been recorded, and this is a matter of considerable moment, for various elaborate discussions of the distribution of velocities within a cross section have assumed the constancy of the instrumental constant for all positions. As clearly indicated by the tabulated results, the constant A increases when the free surface of the water is approached and diminishes when a rigid wall of the conduit is approached.

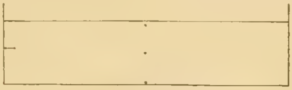

FIGURE 86.—Cross section of prism of water in trough, showing positions given to gage opening in various ratings.

In the application of these results (and of cognate results with which it was thought best not to burden these pages) to our velocity determinations a graphic table was constructed to show the relation of the instrumental constant to the position of receiver in the conduit; and this table (fig. 87) supplied the constant to be used with each individual observation. This procedure had an important influence on the interpretation of the running-water rating, making the apparent correction for that rating less than it would be if the mid-depth constant were used exclusively. Its influence on the vertical velocity curves (figs. 74 to 82) was to give them less curvature near the water surface, greater curvature in approaching the channel bed, and (sometimes) a somewhat lower level of maximum velocity.

In equation (117) $\frac{2g}{2}V^2$ equals twice the theoretic velocity head. If in equation (118) the exponent u be replaced by its mean value 2, we have kV^2 as an expression for the double head actually produced by the gage. The ratio of k to $\frac{2}{2g}$ measures the efficiency of the instrument in realizing the theoretic head. Since $A=\frac{1}{\sqrt{32.28\,k}}$, $k=\frac{1}{32.28\,A^2}$, and the measure of efficiency is

$$\frac{1}{32.28\,A^2}\div\frac{2}{2g}=\frac{32.16}{32.28}\,\frac{1}{A^2}=\frac{0.996}{A^2}$$

The values of the measure have been computed and are given in Table 83. The deep-water and mid-depth ratings being assumed to represent normal conditions, the mean of the corresponding efficiencies, namely, 0.62, may stand in a general way for the fraction of the theoretic head which is realized by this particular type of the Pitot-Darcy gage.

As the relation between velocity and observed head is that between agent and effect, it is evident that values of the efficiency ratio rather than those of the constant A should be compared in any attempt to explain the phenomena of variation. Restating from this viewpoint the results of comparative ratings, we have: The response of the head to changes of velocity is lessened when the receiver of the gage is brought near the free water surface and is increased when the receiver is brought near a rigid part of the stream's perimeter. It may be surmised that the differences in head are connected with the facility with which the flow lines of the water are diverted in passing around the instrument, regarded as an obstruction. In midcurrent the diversion is resisted by the inertia of surrounding water. Near the surface the resistance of water is partly replaced by resistance of more mobile air. Near the conduit the resistance of water is partly replaced by the resistance of an immobile solid.

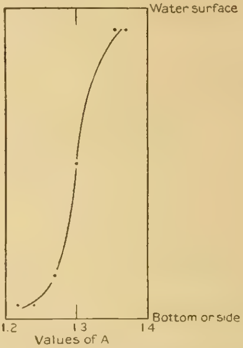

FIGURE 87.—Graphic table for interpolating values of A, in $V=A\sqrt{H-H_1}$, for observations made with gage 3b in different parts of a stream.

APPENDIX B.—THE DISCHARGE-MEASURING GATE AND ITS RATING.

THE GATE.

The gate for measurement of discharge is mentioned at page 20, and its general relation to other apparatus is shown in figure 2. In a section on the measurement of discharge, page 22, it is briefly described, and the history of its use is outlined. Figure 88 is designed to exhibit its relations more fully and shows the arrangement of the general apparatus of the laboratory at the time of its calibration.

The gate controlled an opening in the side of a vertical wooden shaft, of which the internal horizontal section measured 3 feet by 0.5 foot. At the top the shaft communicated freely with a long, narrow tank, to which water was continuously delivered by a pump. The surface level of water in the tank was regulated by means of an overflow weir and a valve above the pump and was observed in a glass tube or gage, *AB*, in figure 88, outside of the tank. This tube was given a slope of 1 in 10, so that the movements of its water column afforded a magnified indication of changes in the water level within the tank.

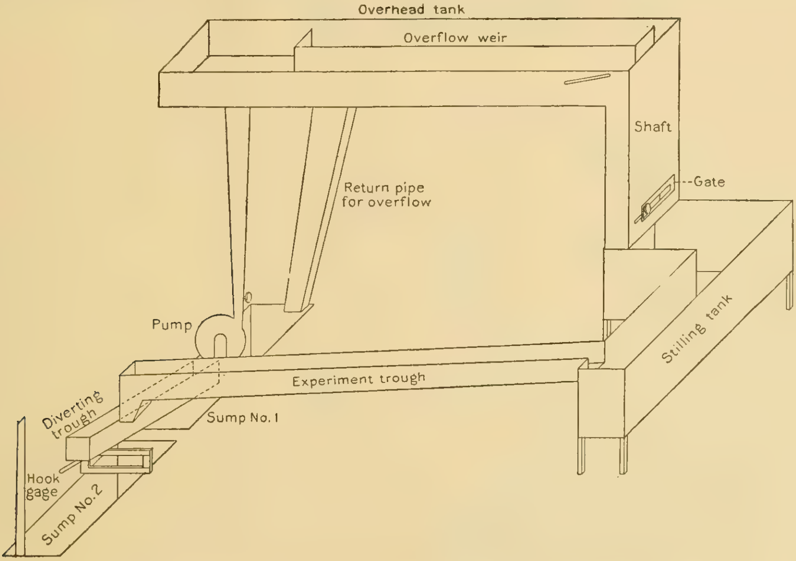

FIGURE 88.—Arrangement of apparatus connected with the rating of the discharge-measuring gate.

Details of the gate are represented to scale in figure 89. A brass plate, *PP*, attached by screws to the outer face of the shaft, was pierced by an opening of 10.5 by 2 inches, the longer dimension being horizontal. About three sides the edges of the opening were beveled outward, leaving a 45° edge at the inner face of the plate. A sliding plate, *G*, rested against the inner face of the fixed plate. This was the gate proper, its function being to close either the whole or a definite portion of the opening and thus regulate the width of the issuing water jet. It overlapped by half an inch the margins of the opening, above and below, and was guided by two brass pieces, which appear in sections *b* and *c*. To the end adjacent to the water jet was given a chisel edge. The brass guides and the adjacent parts of the wooden shaft wall were shaped to a 45° bevel, which, if produced, would reach the edge of the opening in the fixed plate.

Movements of the slide were controlled from the outside. A brass rod, *O*, firmly attached to it and running parallel to its axis (fig. 89*d*), rested in a frame at the left of the opening (fig. 89*a*, *c*), where its motion was controlled by rack and pinion, the rack being cut on the upper side of the rod. At the left of the frame and pinion the rod slid along a brass scale graduated to inches and tenths; and the gate was set for any desired width of aperture by bringing an engraved index mark on the rod opposite the proper mark on the scale.

The operation of the gate was found to be satisfactory.

The head under which the jet issued, measured from the middle of the opening to the water surface in the upper tank, was 6.0 feet, plus or minus a small fraction observed by means of the gage above mentioned.

PLAN OF RATING.

The method of rating was volumetric and empiric. The gate having been set at a particular graduation, and the discharge having been continued until the rate of flow through the stilling tank and experiment trough had become steady, the outflow of the trough was diverted for a measured time into a special reservoir where its volume was measured. The special reservoir is shown in figure 88 as "sump No. 2," and the diverting apparatus also is indicated. The "diverting trough" was pivoted at the remote end and could be turned quickly by hand. In one position it received the discharge from the experiment trough and delivered it to sump No. 1, containing the supply for the pump; in another it permitted the water to fall into sump No. 2, arranged for measurement. The work of rating was performed by J. A. Burgess, and a full report upon it constituted his graduation thesis in engineering at the University of California. The details of apparatus and method were arranged by him, and the following account of the rating is essentially an abridgment of his report.

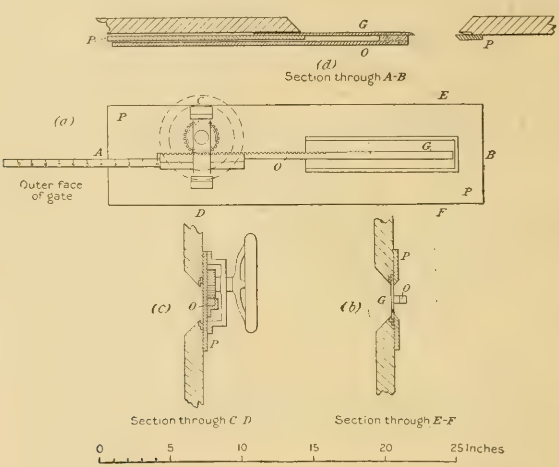

FIGURE 89. Elevation and sections of gate for the measurement of discharge.

CALIBRATION OF THE MEASURING RESERVOIR.

Sump No. 2, constructed of concrete, was approximately rectangular but was not quite regular in form. No attempt was made to base computations of volume on its linear dimensions, but a scale of volumes was graduated directly. A hook gage was first installed, the hook being attached to a vertical rod, to which slow motion could be given. An index borne by the rod near its upper end followed a smooth surface which had been prepared to receive a graduation but initially was unmarked. The index was so arranged that by pressure it could be made to indent the prepared surface, thereby producing a mark of graduation. Starting with just enough water in the sump to permit the use of the hook, a line of graduation was marked. Then a cubic foot of water was added, the hook was readjusted, and a second line was marked. By repeating this process a scale was given to the gage, the unit of the scale being 1 cubic foot. The added units of water were measured in a wooden bottle made in the form of a cube with the opening at one corner; and the volume of the bottle was so adjusted that it contained 62.3 pounds of water. The capacity of the reservoir was about 38 cubic feet.

In the use of the scale thus provided, fractions of a cubic foot were read by means of a small free scale of equal parts applied obliquely to the space between two lines of graduation.

THE OBSERVATIONS.

The record of an observation included (1) the width of gate aperture, (2) the time interval, by stop watch, during which the water was delivered to sump No. 2, (3) two readings of the hook-gage scale, and their difference, giving the volume of water received by the sump, and (4) two gage readings of water level in the upper tank, one just before and one just after the period of volume measurement.

The quotient of the volume of water by the time in seconds gave the discharge for the indicated width of gate opening. The readings of the high-tank water level gave data for a correction to the head, resulting in a small correction to the computed discharges.

It was found that repeated observations with the narrower gate openings gave results nearly identical, while the results for wider openings showed more variation. The observations with wide openings were accordingly multiplied to increase the precision of the averages. The variation was ascribed to pulsations of the flowing water originating in the stilling tank. The general precision of the accepted values of discharge, listed in Table 2 (p. 23), is indicated by an average probable error of ±0.2 per cent. The largest computed probable error is ±0.4 per cent, being that of the discharge for a gate opening of 6 inches.

The general formula for discharge through a rectangular orifice when, as in the present case, the vertical dimension of the orifice is small in relation to the head, is

$$Q = cbd\sqrt{2gh}$$

in which h is the head, measured from the middle of the orifice, bd the area of the orifice, and c the constant of discharge. The observations give the following values of c for different settings of the gate:

Width of gate opening.	Value of *c*.
Inches.	
1	0.704
2	.703
3	.667
4	.677
5	.677
6	.684
Mean.....	.686

For a "standard" orifice 2 inches square and a head of 6 feet Hamilton Smith's tables[1] give 0.604 as the value of c. The inner surface about the standard orifice is vertical and plane, whereas the surfaces about the orifice of our gate were oblique. The oblique guiding surfaces served to increase the velocity at the orifice and thus enlarge the constant of discharge. The variation of the constant with width of opening is probably connected with the fact that the beveled surfaces were not symmetrically arranged about the opening. On three sides they made an angle of 45° with the vertical plane of the orifice, but the edge of the slide, constituting the fourth side, was beveled at a smaller angle. The constants of the gate were thus affected by the conditions of its setting and a new rating would be necessary with a different setting.

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[1] Hydraulics, p. 58.

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PROFESSIONAL PAPER 87

GEOLOGY AND ORE DEPOSITS
OF
COPPER MOUNTAIN AND KASAAN PENINSULA
ALASKA

BY

CHARLES WILL WRIGHT

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PREFACE.

By Alfred H. Brooks.

This report represents the results of an investigation made in conformity with a general plan to survey in detail the important mining districts of southeastern Alaska. This plan was begun by a detailed geologic survey of the Juneau district, completed in 1903,[1] and is being carried out as rapidly as the funds available will permit. The Copper Mountain and Kasaan Peninsula regions were surveyed in 1907 and 1908; the mineralized belt extending from Juneau to Berners Bay in 1910 and 1911.[2]

Meanwhile geologic reconnaissance surveys and preliminary investigations of mineral resources of all the mining districts of southeastern Alaska have been completed and their results published in several reports. There still remain a number of mining districts which should be surveyed in detail. Such work is very expensive because of the high cost of making the base maps in this region of dense vegetation and excessive rainfall. There is also need of more comprehensive study of the stratigraphy of southeastern Alaska. The mining districts which have been surveyed are regions of very complex structure and of igneous intrusion and metamorphism. Therefore these geologic surveys have been more useful in determining the occurrence of the ore deposits than in elucidating the general structure and stratigraphic sequence in the province. Plans are under consideration for a more exhaustive study of the stratigraphy of this province which it is hoped can be put into execution before long.

In 1909 Mr. Wright left the United States Geological Survey to take up private work in Sardinia, a fact that accounts for the long delay in the completion of this report, which has been prepared at such times as he could spare from his professional work. This delay is regrettable, but meanwhile the interests of the mining industry in this field have not been lost sight of, for the more important economic conclusions and the geologic maps were promptly prepared by Mr. Wright and published.[3] In justice to Mr. Wright it should be stated that he submitted this report in final form in September, 1912, but that a further delay in its publication was caused by the lack of funds for printing.

The descriptions of the developed ore bodies and mine workings here given must be regarded in the main as representing the information at hand up to the close of 1908. Since 1908 important discoveries and developments have been made on some of the properties here described, but these will only in part be referred to in this report. In the early part of 1914 some large operations on copper properties were begun in the Ketchikan district, but the collapse of the copper market led to the suspension of much of this work.

---

[1] Spencer, A. C., The Juneau gold belt, Alaska: U. S. Geol. Survey Bull. 287, 1906.

[2] Knopf, Adolph, Geology of the Berners Bay region, Alaska: U. S. Geol. Survey Bull. 446, 1911; The Eagle River region, southeastern Alaska: U. S. Geol. Survey Bull. 502, 1912.

[3] Wright, C. W., Mining in southeastern Alaska: U. S. Geol. Survey Bull. 379, pp. 75-82 and Pls. II and III, 1909.

GEOLOGY AND ORE DEPOSITS OF COPPER MOUNTAIN AND KASAAN PENINSULA, ALASKA.

By Charles W. Wright.

INTRODUCTION.

Location of areas described.—Kasaan Peninsula and Copper Mountain are now (1912) the two most important copper-bearing areas in southeastern Alaska. The first is a peninsula projecting into Clarence Strait from the east side of Prince of Wales Island; the second is a small area which encircles the base of Copper Mountain, on the west side of Prince of Wales Island, and which is readily accessible to ocean traffic by the upper part of Hetta Inlet. Both areas lie within the Ketchikan district or precinct. The town of Ketchikan, which is east of Clarence Strait, is the recording office of the district and an important commercial center.

Scope of report.—It is proposed to consider in detail the geology of Copper Mountain and Kasaan Peninsula. Special attention will be paid to the occurrence of contact ore deposits, which are well exemplified in this region. The mining development will be only briefly described, as it is not of permanent interest and is, moreover, fully treated in the Geological Survey's annual bulletins showing the progress of investigations of the mineral resources of Alaska. The detailed descriptions will be prefaced by a general account of the geology of the Ketchikan district, which is considered essential to an understanding of the details that follow.

Surveys and explorations.—Brief references to the occurrence of copper and other ores in the districts here under consideration appear in some of the earlier publications treating of southeastern Alaska. The first systematic study of this field was made in 1901 by Alfred H. Brooks. The resulting report [1] outlined the general geology of the Ketchikan district and briefly described some of the newly discovered copper deposits of Kasaan Peninsula and Copper Mountain. A more extensive geologic survey of this field was made by F. E. Wright and the writer in 1904 and 1905, and a report [2] on this work described at some length the geology and mineral resources of the Ketchikan district and included brief accounts of the ore deposits of Copper Mountain and Kasaan Peninsula.

All the above work was done without base maps, except the charts delineating the shore line. In 1907 and 1908 D. C. Witherspoon, J. W. Bagley, and R. H. Sargent made a detailed topographic survey of the Kasaan Peninsula.[3] Mr. Sargent made a similar survey of the Copper Mountain region in 1908.[4] These surveys were made on a scale of 1:45,000, and the results have been reduced for publication to a scale of 1:62,500. The contour interval on the map of Kasaan Peninsula is 50 feet, on the map of Copper Mountain 100 feet. The details of relief and drainage are shown with much precision. The mines and prospects are indicated by conventional symbols, as are also the wagon roads and trails.

Geologic study was begun in 1907 by the writer, assisted by Sidney Paige, when a part of the Kasaan Peninsula was covered. The mapping of this area was completed by the writer in

---

[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska, with an introductory sketch of the geology of southeastern Alaska: U. S. Geol. Survey Prof. Paper 1, 1902.

[2] Wright, F. E. and C. W., The Ketchikan and Wrangell mining districts, Alaska: U. S. Geol. Survey Bull. 347, 1908.

[3] Topography of Kasaan Peninsula, Prince of Wales Island, Alaska: U. S. Geol. Survey Alaska Sheet No. 540B, 1911.

[4] Copper Mountain and vicinity, Prince of Wales Island, Alaska: U. S. Geol. Survey Alaska Sheet No. 540A, 1911.

1908, as was also the geologic work in the Copper Mountain region. A total of six months in two seasons was spent on the work. During this time geologic surveys of about 86 square miles in Kasaan Peninsula and 45 square miles in the Copper Mountain region were made.

Although the preparation of the final report on this work has been long delayed, the geologic maps [1] and the results that bear on the occurrence of mineral deposits were published promptly and will be freely used in this report.

Geologic maps.—The general geologic map of the Ketchikan district (Pl. I) accompanying this report is only slightly modified from one previously published [2] which was prepared by F. E. Wright and the writer.

On the detailed geologic maps (Pl. V, p. 30, and Pl. XV, in pocket) the boundaries of the rock formations, where actually observed in the field, are indicated by solid lines; where only inferred, by broken lines. As outcrops are exceedingly scant in this moss-covered and timber-covered area, the distribution of the formations as indicated on the maps is in large measure only approximately accurate. If a contact between two formations is important in the search for ore bodies its exact position should be determined on the ground by stripping before extensive mining operations are begun.

This report includes a number of maps of mining properties and mine workings which have been furnished by the operators, the geology having been added by the writer.

Acknowledgments. The field and office work for this report has been done under the direction of Alfred H. Brooks, to whom the writer is indebted for many valuable suggestions. To Fred. E. Wright and particularly to H. E. Merwin, of the Geophysical Laboratory of the Carnegie Institution of Washington, he is indebted for extensive petrographic studies. The stratigraphic and paleontologic studies of E. M. Kindle in this field have also been of great value. In the field work on Kasaan Peninsula in 1907 the writer was ably assisted by Sidney Paige, to whom much credit is due for geologic mapping. To the mine owners, operators, and prospectors of the districts, all of whom extended a hearty cooperation in the work and many personal courtesies, the writer is most grateful. Though impossible to mention all who aided in this investigation, the work was especially facilitated by U. S. Rush, of Kasaan; N. O. Lawton, of Hadley; W. B. Freeburn, of Mount Andrew; and Charles A. Sulzer, of Sulzer. Acknowledgment must also be made to the firm of Winter & Pond, of Juneau, for permission to use certain photographs here reproduced.

KETCHIKAN DISTRICT.

TOPOGRAPHY.

GENERAL FEATURES.

The Ketchikan district includes about 7,200 square miles in the southernmost part of southeastern Alaska. It embraces two distinct topographic provinces, the more rugged being the eastern or mainland belt and the adjacent islands, the largest of which is Revillagigedo, and the other, which has less strong relief, including Prince of Wales and some smaller islands. The coast line of the district is broken by innumerable straits, fiords, and minor indentations. The longest fiord, Portland Canal, which marks the boundary between Alaska and British Columbia, extends about 150 miles inland and is everywhere bounded by steep mountain slopes.

MAINLAND.

The general topographic aspect of the eastern or mainland portion of the Ketchikan district is similar to that of the other portions of the Coast Range province lying on the north and south. The mountains rise abruptly—at some places in sheer cliffs from tidewater to elevations of 2,000 to 5,000 feet, and the peaks farther inland reach altitudes of 6,000 to 10,000 feet. These mountain masses are for the most part made up of immense batholiths of the granite of the

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[1] Wright, C. W., and Paige, Sidney, Copper deposits on Kasaan Peninsula, Prince of Wales Island: U. S. Geol. Survey Bull. 345, pp. 98–115, 1908; also, Wright, C. W., Mining in southeastern Alaska: U. S. Geol. Survey Bull. 379, pp. 67–86, 1909. The geologic maps in this paper form Pl. II (p. 76) and Pl. III (p. 80).

[2] Wright, F. E. and C. W., The Ketchikan and Wrangell mining districts, Alaska: U. S. Geol. Survey Bull. 347, Pl. I.

Coast Range, and the land features are chiseled on a corresponding broad scale. Because of the mode of formation and physiographic development of these mountains there is in general a decided lack of bedrock control of the lines of drainage or erosion. Though profoundly dissected, the mountains show a notable tendency to uniformity in the elevation of their crest lines. The summits are generally broad and somewhat flat, and their backs are gently arched so that if the steep-sided valleys were filled to restore their original profiles, the region would present an undulating surface sloping gradually westward from the center of the range.

The form of the land indicates that the region has been intensely glaciated and but slightly modified by water erosion since the glacial epoch. At the time of its maximum extent the ice sheet covered the whole area except some isolated high peaks, which can now be identified by their sharp, serrated outlines—their lack of glacial rounding. Even during the present period of glacial drought a number of small ice fields still exist here in the Coast Range belt, lying above the snow line and sending small tongues down the valleys even to tidewater. The region contains abundant and striking features of glacial sculpture, such as U-shaped valleys, fiords, glacial erratics, cirques, hanging valleys, double-cliff slopes, truncated spurs, alignment of cliff bases, and glacial grooves and striæ. The notable absence of moraines in this area of extensive glaciation is due chiefly to the steepness of the slopes of the mountains and valleys. Many of the fiords are floored with sand and gravel moraines, and some of them are partly choked at their entrances by morainic material. Forelands occur here and there, but they are small, and the region includes no large areas of level land. The peninsulas and the adjacent islands are more or less separated from the mainland by deep, narrow fiords extending many miles inland and they contain mountains whose summits range in height from 2,000 to 4,000 feet above sea level.

The mainland belt is intricately dissected by narrow, steep-sided valleys heading in canyons, many of which are filled with snow, or in glacial cirques, a number of which contain small glaciers or patches of ice. The initial descent of these valleys is steep, the streams in places forming beautiful waterfalls of considerable volume. Farther down the slopes tributary creeks or rivers enter these streams from both sides, the valleys gradually widen, and the valley floors become covered with a gravel wash consisting largely of gravel, cobbles, and bowlders of granite. As the grade decreases the gravel beds become deeper and wider, and the stream flows around the flanks of precipitous mountain spurs and enters the sea at the head of some tidewater inlet. The tidal flats at these points are usually wide and are composed of deep fine sand and mud, the depth to bedrock being probably several hundred feet. They extend into the channels for a short distance beyond the low-tide line and there end abruptly. Depths of 50 to 100 fathoms are common in these inlets a short distance from the shore.

The seaward extension of many of these valleys is represented by tidewater channels or fiords. The largest of these in this region is Portland Canal, which penetrates the mainland for some 150 miles, with an easterly and then a northerly course. From its sides the mountains close at hand rise to elevations of 4,000 to 6,000 feet. Bear and Salmon rivers discharge into the head of this canal.

PRINCE OF WALES ISLAND.

There are no topographic maps of Prince of Wales Island, and little is known in detail of the courses of its valleys or of its mountain ranges. Its eastern shore line has been charted by the Coast and Geodetic Survey, but the mapping of the western coast is still incomplete.

Prince of Wales Island is 80 miles long and 30 miles wide, and is separated from the mainland by Clarence Strait, a deep channel 5 to 10 miles wide, trending about north and south. Its shore line is indented by numerous bays and inlets, which are characteristic of the entire coast. Portions of its west coast are directly exposed to the Pacific Ocean, but most of it is protected by small seaward islands, the largest of which is Dall Island. Viewed from the channels Prince of Wales Island presents a mountainous mass of very irregular outline. Its relief, however, is less rugged than that of the mainland or of some of the islands to the north, such as Baranof Island. A low pass across the island, 4 miles long and less than 150 feet high, connects the head of Cholmondeley Sound on the east coast with the head of Hetta Inlet on the west coast.

Another pass, 6 miles long, unites the south arm of Cholmondeley Sound with Klakas Inlet. The head of Twelvemile Arm also is connected with Big Harbor on the west coast by a portage several miles long. There are also probably other low gaps between the east and west coasts of the island. Numerous lakes occur on the island both in low-lying valleys and in basins lying at elevations of 1,000 to 2,000 feet. The mountain summits range in height from 2,000 to over 3,000 feet, one of the highest being Copper Mountain, 3,900 feet above sea level.

In general both the course of the valleys and the trend of the small mountain ranges of this island conform to the underlying rock structure, which has largely controlled the erosive processes. The intrusive masses and limestones usually persist above the general level and form the hills, ridges, and mountain peaks. The areas of shales, sandstones, and other less resistant rocks are marked by lowlands, deep valleys, and channels.

There are now no glaciers on Prince of Wales Island, but evidence of former glaciation is everywhere present. Basins scooped out by glacial action and now filled with lakes occur at elevations of a few hundred to 2,000 feet in the vicinity of Copper Mountain, and the surrounding mountains, composed essentially of granite, are well rounded and bear many large bowlders that are evidently erratics. In the Klawak Range, farther north, there are several clearly defined glacial cirques containing small lakes and surrounded by more or less jagged crest lines. Grooves observed at a few places on rocks exposed along the tidewater channels may also be attributed to glaciation.

The coast line of this and adjacent islands is broken by bays, coves, and channels. The charts of this area show numerous excellent harbors and many protected channels that favor navigation. One of the striking features is the shallowness of many of the bays and channels as compared with the depths noted in the fiords of the mainland belt. Again, the river deposits at the heads of bays have a gradual slope; they do not descend abruptly into deep water a short distance from the shore, as do the tidal flats along the mainland. These facts and the topographic observations tend to show the greater advance in topographic development of the seaward part of the region in contrast with that of the mainland.

CLIMATE.

The annual changes in climatic conditions in southeastern Alaska are not so varied as might be expected in a region lying between 55° and 60° north latitude. The effect of the warm waters of the northern Pacific is strongly felt and serves to moderate the climate. The region is characterized by mild winters and cool summers. The mean annual temperature is about 45° F. The mean temperature of the three summer months is about 55° F.; of the three winter months about 35° F. The precipitation is heavy and is greatest where high mountains abut on the sea. Nearly all the precipitation below an elevation of 500 feet is in the form of rain. Rainfall records in the Ketchikan district are scant, but indicate a total precipitation of about 98 inches at Shakan, near the north end of Prince of Wales Island, and of 148 inches at the town of Ketchikan. Most of the rain falls between the first of September and the last of January, though the amount varies greatly from year to year. The season of least rainfall is generally from April to July. The snowfall is heavy in the mountains, from 3 to 8 feet in depth, but near sea level not more than a few inches of snow falls at one time during an ordinary winter, and this soon disappears.

The prevailing winds come from the southwest and bear moisture from the sea, which condenses in the form of fog and rain about the mountain range. The abundant precipitation is trying to those who are accustomed to a more arid climate, but this rainfall, though a drawback to the prospector, does not interfere with mining development. It is an advantage, for it furnishes water power which can be utilized in mining operations.[1] Except at high altitudes snow does not interfere materially with transportation or mining.

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[1] Hoyt, J. C., A water-power reconnaissance in southeastern Alaska: U. S. Geol. Survey Bull. 442, pp. 147-157, 1910.

VEGETATION.

The growth of timber and vegetation along the coast of southeastern Alaska is almost as dense as that of a tropical region. Its luxuriance is caused by the moist and temperate climate and the long summer days of this latitude. At elevations below 1,500 feet bushes, ferns, and tall grasses grow profusely, especially in the valleys and gulches. In places these form a dense and almost impassable undergrowth and are a great hindrance to the prospector. The timber is almost entirely of coniferous species, principally western hemlock and spruce, and is in general of an inferior grade, suitable only for rough work. The timber line ranges in elevation from 1,500 to 2,500 feet, but most of the large trees grow at low altitudes. The stands of commercial timber vary greatly, ranging from 30,000 to 80,000 feet (board measure) per acre. The average run of saw timber in southeastern Alaska, however, because of the scant growth in the swamps and on the higher slopes, is not more than 5,000 to 10,000 feet per acre.

The hemlock is used for piling, but most of the lumber cut in the local sawmills is spruce. The cedar is not sufficiently abundant to have much value. The entire Ketchikan district lies in the Tongass National Forest.

There are some good agricultural lands in the flats, but they are of small extent. Some of them have been successfully utilized for gardening, for which use the climate and soil are favorable.

COMMERCIAL CONDITIONS.

Ketchikan, the prosperous commercial center of the district, is on the west side of Revillagigedo Island, which lies close to the mainland about 15 miles east of Prince of Wales Island. It has a population of about 1,500 and is provided with all necessary municipal improvements. It is an important fishing center and has ample wharves, good hotels, banks, and stores. It is connected by cable with Seattle and with Alaska ports. Supplies can be purchased at little advance over Seattle prices. Coal is brought from Vancouver Island and retails at about $8 a ton (1908).

Communication is maintained between the mining camps and Ketchikan by steamships and launches. Ketchikan is 52 hours from Seattle by steamships following the inside passage, three to five entering the port every week from the States. Direct weekly steamship connection is also maintained with Vancouver, British Columbia. Prince Rupert, the western terminal of the Grand Trunk Pacific Railway, to be completed in 1915, is only 5 hours by steamer from Ketchikan.

The timber supply of the region is adequate for all mining purposes. The local sawmills furnish rough lumber, and good timber for piling is abundant. There are also some good water powers in the district, though they are but little developed. The irregular coast line affords many good harbors, which are free of ice throughout the year. As a general rule the country is one of strong relief, which is favorable to mining developments through adit tunnels and without hoisting.

The conditions in general in the district are exceptionally favorable to mining operations and, except for the irregularity of some of the ore bodies, are almost ideal for reducing operating costs to a minimum.

PRODUCTION OF COPPER.

The occurrence of copper deposits on Kasaan Peninsula was known even during the Russian occupation, but small heed has been paid to them except in very recent years. An attempt was made to establish a copper-mining industry near the present site of Kasaan in 1879–80, but it was abandoned after a few tons of ore had been mined and shipped. The copper now produced in the Ketchikan district is derived almost entirely from mines on Kasaan Peninsula and about Copper Mountain. The growth of the copper-mining industry in this field is shown in the following table:

Ore production from copper mines in the Ketchikan district, 1905–1911.

Year.	Ore mined.	Copper.		Gold.		Silver.		Average value of ore per ton.
		Amount.	Value.	Amount.	Value.	Amount.	Value.	
	Tons.	*Pounds.*		*Ounces.*		*Ounces.*		
1905	30,400	1,901,392	$295,616	1,178	$34,370	13,000	$7,867	$10.79
1906	85,139	4,350,571	838,660	3,031	62,851	27,152	18,102	10.81
1907	79,982	4,758,814	951,761	3,384	69,960	44,196	29,143	13.14
1908	43,215	3,260,399	430,372	2,213	46,310	24,648	13,063	11.10
1909	28,491	2,705,988	351,778	1,946	40,228	16,679	8,641	14.06
1910	27,425	2,254,487	286,320	1,503	31,081	14,598	7,884	11.86
1911	13,753	977,468	120,719	613	12,678	6,573	3,484	9.95
1912	13,494	1,234,888	203,756	1,080	22,335	10,035	6,171	17.21
1913	7,276	599,903	92,985	484	10,000	4,447	2,686	14.52
	329,175	22,043,900	3,571,967	15,432	329,813	161,328	97,041	12.15

The copper production of the district previous to 1905 is estimated at 1,600,000 pounds. At 12 cents a pound, the average price of copper for the period in which it was mined, the value of this output is $192,000. These amounts, added to those for 1905 to 1913, give a total copper production of 23,643,900 pounds and a total value of $3,763,967.

Practically the first large shipments of ore were made in the spring of 1905. The rise in the price of copper from an average of $0.156 a pound in 1905 to an average of $0.20 a pound in 1907 permitted the profitable extraction of copper ores of low grade averaging 59 pounds per ton, and with the improvements in methods of transportation and mining the production was much increased. In 1908 the average price of copper dropped to $0.132, and this led to the closing down of some of the principal producing mines. Of ten producing mines in 1907 only five were operated in 1908 and only three or four during the following years. From these the average copper content per ton of the ore shipped was about 90 pounds. In 1911 only three mines were producing, and the ore shipped yielded on an average 70 pounds of copper per ton.

GEOLOGY.

GENERAL FEATURES.

The geology of the Ketchikan district is but imperfectly known, for, except in the two areas to be described in detail below, observations have been confined almost entirely to the shore lines, and this limitation, together with the gaps in the information regarding continuity of formations and stratigraphic relations caused by the many broad waterways, has prevented the exact determination of either stratigraphic sequence or structure. Hence the sedimentary rocks of the region, which range in age from Silurian to Jurassic or Cretaceous, will be described in only a general way, but as the knowledge of the igneous rocks is more exact and comprehensive, these will be described in greater detail.

The geologic map (Pl. I) shows that the intrusives of the Coast Range occupy a larger area than any other of the rock units that have been discriminated. The main batholiths of these intrusives occupy the eastern part of the district and form a convenient starting point for a geologic description, though they by no means represent the oldest rocks of the district. Adjacent to these intrusives on the west and in part included within their area lies a series of crystalline schists which, though in places showing igneous phases, are for the most part sedimentary. The seaward and western boundaries of these schists are marked by a belt of argillites—either slates or phyllites—in part interbedded, in part succeeded by ancient lavas and tuffs that are here grouped together as greenstones. Some semicrystalline limestone bands occur in this slate and greenstone series, and as Carboniferous fossils have been found in these limestones the entire sequence has heretofore been referred to the Carboniferous period. This determination of the age of the series accords with Spencer's[1] provisional determination of the age of similar rocks that apparently represent a northern extension of the same belt. Knopf's[2]

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[1] Spencer, A. C., The Juneau gold belt, Alaska: U. S. Geol. Survey Bull. 287, p. 17, 1906.

[2] Knopf, Adolph, The Eagle River region, southeastern Alaska: U. S. Geol. Survey Bull. 502, pp. 17–18, 1912.

U S GEOLOGICAL SURVEY
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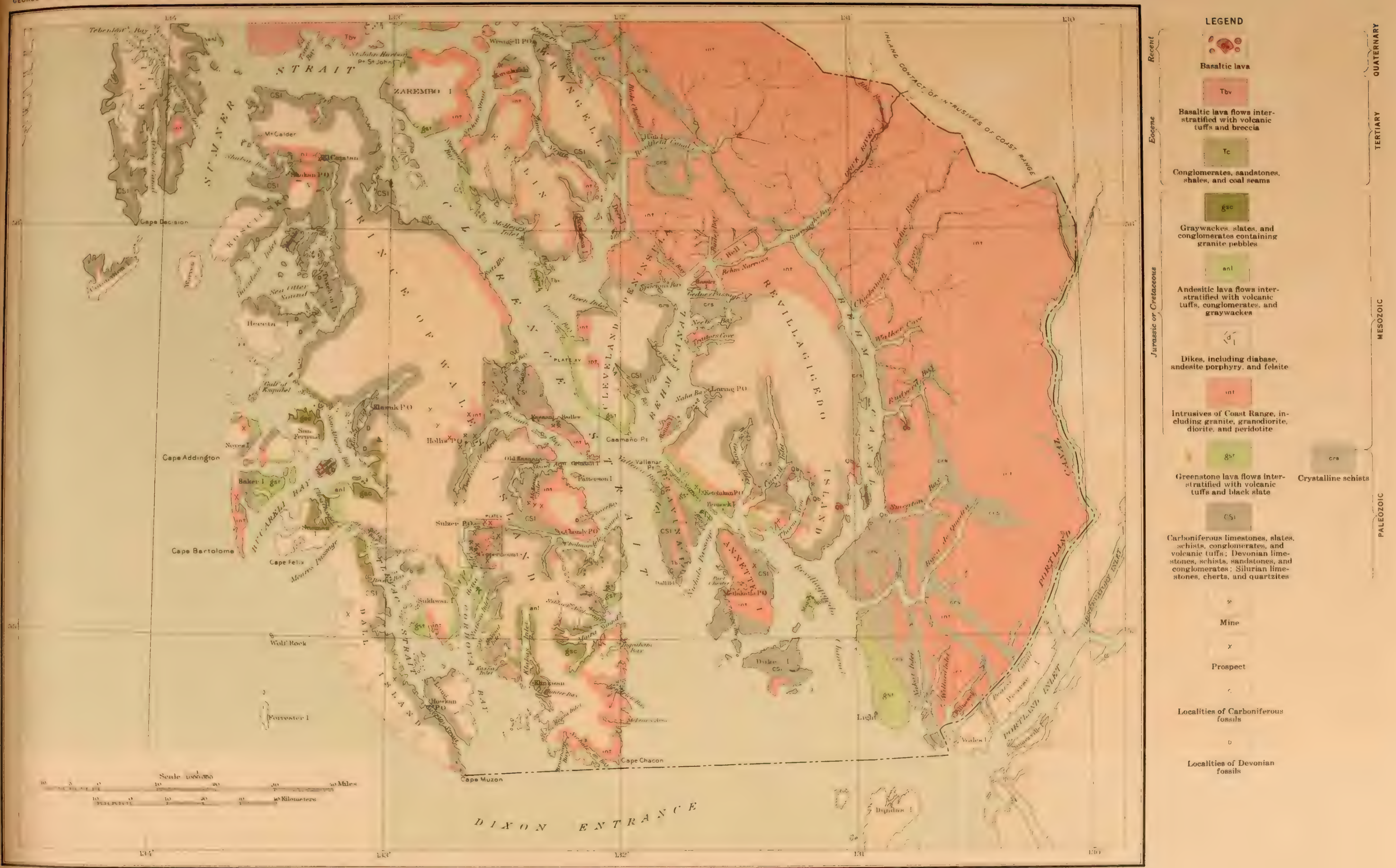
PROFESSIONAL PAPER 87 PLATE I



GEOLOGIC RECONNAISSANCE MAP OF THE KETCHIKAN AND WRANGELL MINING DISTRICTS, SOUTHEASTERN ALASKA

By F. E. and C. W. Wright

1914

Base compiled chiefly from charts of
U S Coast and Geodetic Survey

House Doc. ; 63d Cong., 2d Sess.

recent studies north of Juneau have shown, however, that these rocks are in part, at least, of Jurassic or Lower Cretaceous age. This series of slates, phyllites, schists, and greenstones may therefore be Mesozoic, though it may include some infolded Carboniferous limestones. On the map the sedimentary rocks adjacent to the Coast Range are not differentiated from the sedimentary rocks that lie farther west, most of which are older than those near the Coast Range.

But few correlations have been made between the rocks of Prince of Wales and adjacent islands and those of the mainland belt described above. Igneous rocks like those found in the Coast Range occur as intrusives in this western province. Some of the sedimentary rocks here are also lithologically the same as some of those found farther east, and the likeness suggests certain correlations which can not yet be definitely established. The sedimentary rocks of Prince of Wales Island include slates, quartzites, arkoses, and conglomerates, and locally a large amount of limestone. The fossils found in these rocks indicate the presence of strata ranging in age from Silurian to Carboniferous. The rocks of the island include also a series of volcanic deposits and another of graywackes and conglomerates, which on stratigraphic grounds have been assigned to the Mesozoic. The Paleozoic formations have not been differentiated on the geologic map (Pl. I), which therefore indicates a sameness in the geology of Prince of Wales Island that is by no means in accord with the facts. The continuity along strike lines that is characteristic of the mainland does not prevail on Prince of Wales Island, where the rocks show close folding, which, with the presence of many large stocks of igneous rocks, has given great variety to the geology. The Tertiary period is represented in the district by one small area of conglomerate, sandstone, and shale; the Quaternary by many widely distributed basaltic lava flows, though none of any great areal extent.

Of the igneous rocks the intrusives of the Coast Range, made up of granite, diorite, granodiorite, and peridotite, are most abundant and most widely distributed. These are believed to be of Mesozoic age. Dikes of diabase, porphyrite, and felsite are widely distributed and are probably later intrusives.

SEDIMENTARY ROCKS.

PALEOZOIC STRATA.

Little or nothing is known of the oldest rock formations in the district, but it is doubtful whether they include pre-Paleozoic strata. The crystalline schists and gneissoid rocks, which form a wide band adjacent to the Coast Range and resemble the ancient metamorphic clastics of other regions, are mostly of late Paleozoic and early Mesozoic age, and their present crystalline condition is attributed to metamorphism caused in part by the intrusives of the Coast Range.

The sedimentary record begins with the Silurian, which is represented by fossiliferous limestones. These limestones include thick strata of banded graywacke, and the limestone and graywacke together form a belt that is exposed at points on the west coast of Prince of Wales Island and on Kasaan Peninsula. The banded graywackes are nearly everywhere extremely fine-grained or aphanitic, indurated, clastic rocks, gray to green in color, very brittle, with little or no cleavage. They include both sedimentary strata and indurated beds of tuff with mixed sedimentary material. Weathering usually produces a brown surface by the oxidation of pyrite and other ferruginous particles. The total thickness of the beds can not be estimated because of complicated folding, though it must amount to many thousand feet.

At the base of the Devonian lie thick beds of conglomerate containing pebbles and cobbles derived from the older Silurian beds, and indicating that an unconformity occurs between the Silurian and Devonian strata, though the rocks of these two periods were not observed in contact.

At many places along the northwest shore of Prince of Wales Island and on the smaller islands adjacent to Davidson Inlet a thick series of limestones overlies these beds of conglomerate, and together the two series represent the lowest horizon of the Devonian system. The conglomerates consist essentially of cobbles of banded quartzite and some fragments of limestone and schist. Toward the limestone beds they grade into sandstone and slaty limestone. They are conformably overlain by the limestones. Narrow beds of the sandstone are also interstratified with the beds of limestone. The limestones are semicrystalline and gray to blue in color, and not many of the fossils in them are identifiable. At several points, however, imperfect fossils, which have been referred to the Devonian, were gathered, the largest collection having been obtained on the east shore of Haceta Island, from beds directly overlying the conglomerates.

The total thickness of the conglomerate beds is estimated at 1,200 feet and that of the overlying limestone beds at 1,800 feet. At this locality the strata are broadly folded and the rocks are considerably metamorphosed.

A somewhat higher horizon of the Devonian is represented by the limestone beds on Long Island, in Kasaan Bay, on the east side of Prince of Wales Island. At this locality both Lower and Middle Devonian faunas have been recognized, though the limestone strata containing them are apparently conformable.

The stratigraphic relations of the limestones of Long Island to the beds on the adjacent shore of Kasaan Bay can not be definitely determined because of their topographic isolation.

The Middle Devonian horizon occurs again about 20 miles south of Long Island, at the head of Clover Bay, where there is a small area of schistose argillites and black limestone almost completely surrounded by an intrusive mass of diorite. These beds are highly tilted and have a general easterly strike.

At Vallenar Bay, on the north end of Gravina Island, beds of shaly limestone, argillaceous schist, and schistose conglomerate containing a Middle Devonian fauna occupy the crest of an anticline. These beds underlie the slates and greenstones which border the east and west shores of the island. The Devonian beds at this locality and those on Long Island were included under the name Vallenar series by Brooks in his report on the Ketchikan district.[1]

Limestone beds containing an Upper Devonian fauna and overlying with apparent conformity banded argillaceous beds, similar to those of Middle Devonian age exposed at Clover Bay, occur on San Juan Bautista Island and in Klawak Inlet, on the west coast of Prince of Wales Island.

The distinctions between the three divisions of the Devonian—the Upper, Middle, and Lower—in most places are not clearly defined paleontologically, and at no locality was a complete section of these horizons obtained.

The stratigraphic relations between the early Carboniferous and the late Devonian formations are not definitely known, and in no place were the formations observed together. The early Carboniferous is represented by fossil-bearing limestones on an islet at the entrance to Soda Springs Bay, on the west coast of Prince of Wales Island. The limestone beds strike north and are steeply tilted toward the east. They overlie with apparent unconformity conglomerates and sandstones that resemble those of early Devonian age. On Prince of Wales Island opposite this islet there are slates and chlorite schists which resemble those probably belonging to the slate and greenstone series of Copper Mountain.

Fossils were found in beds of calcareous shale that outcrop on the south end of Gravina Island, 3 miles north of Dall Head. These fossils were fragmentary and could not be definitely determined, but are provisionally referred to the early Carboniferous. They may, however, represent a Triassic horizon.

Few data exist concerning the interval between the early and late Carboniferous faunas, as the rocks containing the two faunas are nowhere present at the same locality and no fauna representing the intervening epoch has been found. The upper Carboniferous, which probably includes the most extensively developed formations, is represented by fossiliferous limestone beds at George Inlet, within the mainland belt, and at several points on the islands. In the mainland belt the limestones are included in a succession of argillites and crystalline schists, which are closely folded and highly metamorphosed and form a band about 10 miles wide adjacent to the intrusives of the Coast Range. These metamorphic strata, called by Brooks [1] the Ketchikan series in this province, probably include several formations, which, however, have not been defined because of the complexity of their structure and the extent of their metamorphism. They probably include formations as old as the Carboniferous and as young as the Jurassic (see p. 16), but the subdivisions have not yet been differentiated. Similar rocks are widely distributed, not only on the mainland and adjacent islands but on the west coast of Prince of Wales Island.

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[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, pp. 42-43, 1902.

The most recent of these metamorphic rocks are the greenstone lava and tuff beds interstratified with beds of black slate. The structural relations of these beds to the older and younger rocks indicate that they are upper Carboniferous or Mesozoic, as they overlie the limestones (Carboniferous) and schists with apparent conformity. Similar rocks in the Juneau district were described by Spencer [2] as the "slate-greenstone band." Knopf's recent work has shown that these sediments in the Juneau district are probably of Jurassic age and has correlated them with the Berners formation, made up of slates, graywacke, and some greenstones.[3]

The greenstone and slate series of the Ketchikan district trend in many places parallel to the older limestones and schists, although they exhibit many local variations in strike and dip. Their total thickness is estimated to be over 4,000 feet. They occur principally along the outer border of the mainland belt in Tongass Narrows and on Cleveland Peninsula, but they also form a smaller belt along the west coast of Prince of Wales Island.

As a whole, the greenstone members of this slate and greenstone series predominate over the slate or the sedimentary beds, but the relative proportion varies from place to place, presumably because of inequality in the distribution of the lava flows and tuffs. The igneous and sedimentary material in these beds is intimately associated in varying amounts and grades from altered andesitic lavas and tuffs to purely sedimentary beds.

MESOZOIC STRATA.

The formations in the Ketchikan district that have been referred to the Mesozoic era contain no fossils, and the determination of their age is therefore based entirely on their structural and petrographic features. The possible Mesozoic age of the slate and greenstone series has just been indicated.

So far as known, the intrusives of the Coast Range, which occupy about half the land area of southeastern Alaska, invaded the bedded formations early in the Mesozoic era. These intrusives are discussed under the heading "Igneous rocks" (p. 20).

At the south end of Prince of Wales Island there is a series of andesitic flows, conglomerates, and tuffs, which grade into a series of graywackes or indurated sandstones, including some beds of slate. These rocks have been considered Mesozoic because of their structural and petrographic relations to the older rocks. In this series basaltic and andesitic flows are intercalated with tuffaceous beds, and both flows and tuffs alternate with the sedimentary slates, graywackes, and conglomerates. The rocks of the series are readily distinguished from the greenstones by the wide difference in the composition and texture of the interstratified beds and by their predominant reddish color. A fine, compact green tuff is usually overlain by an andesitic lava containing numerous large plagioclase phenocrysts, which is in turn overlain by a basaltic lava or a red lava conglomerate. The greenstone beds, on the other hand, vary little in composition and, where massive, augite crystals form the phenocrysts.

On the south end of Prince of Wales Island the andesitic flows and conglomerates overlie at several points the eroded surfaces of granitic intrusive masses, and numerous dikes of the andesite intrude these older granites. Pebbles and fragmentary masses of the granite were observed in the tuffaceous conglomerates, showing clearly that the andesites are younger than these masses of granite rock. The granites at this point were more altered and contained more shearing planes than are generally found in the intrusives of the Coast Range, and they may represent a batholith intruded before or during the earliest stages of the granitic invasion of that range. The graywackes overlying the andesites are compact and indurated but show no schistosity. Pebbles of granodiorite, quartz, andesite, and graywacke are plentiful in the conglomerates. These beds as a whole, though tilted at steep angles and folded, have not suffered the intricate folding and metamorphism seen in the older rock beds, including those of the Sitka district. No fossils were found in these beds, but the facts above stated indicate that they occupy a position in the stratigraphic column between the Triassic and the Upper Cretaceous. It is possible that their horizon may be the same as that of the slate and greenstone found adjacent to the Coast Range batholith. (See p. 16.)

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[1] Brooks, A. H., op. cit., pp. 44–45.

[2] Spencer, A. C., op. cit., pp. 16–17.

[3] Knopf, Adolph, The Eagle River region, southeastern Alaska: U. S. Geol. Survey Bull. 502, pp. 13–14, 1912.

TERTIARY STRATA.

Tertiary beds are widely distributed along the Pacific seaboard of Alaska, though their total areal extent is comparatively small. In the Ketchikan district they are found only on Prince of Wales Island, where they occupy a small basin at Coal Bay, a southern arm of Kasaan Bay.

The Tertiary rocks comprise conglomerates, sandstones, and impure lignitic coal seams. They are soft, friable, and unmetamorphosed. There are very few exposures of these rocks, but judging from the better-developed Tertiary beds to the north they are probably but little disturbed.

RECENT DEPOSITS.

The few Recent deposits in the districts under discussion consist of stream gravels covering narrow valley bottoms and somewhat more extensive deposits at mouths of deltas. Some stream terraces noted on Kasaan Peninsula are probably underlain by gravels. Most of the beaches are rocky, consisting generally of almost shear cliffs, but locally some small sand and gravel beaches have been developed. In places in tidal flats there are also some more extensive deposits of fine alluvium. Glacial deposits of various types also occur in the Ketchikan district. None of these Recent deposits is indicated on the accompanying geologic maps.

IGNEOUS ROCKS.

CLASSES DISCRIMINATED.

The igneous rocks include (1) the intrusive masses, such as the dioritic and granitic batholiths, gabbros, and peridotites which invade the sedimentary rock beds; and (2) the extrusives, or those which represent surface lava flows, such as the greenstones, andesites, and basalts. The most abundant and important of the igneous rocks are the granitic intrusives of the Coast Range, which occupy about one-half of the aggregate land area of the district.

INTRUSIVES OF THE COAST RANGE.

GENERAL FEATURES.

The Coast Range massif as it has been defined by Dawson is not of the same composition throughout, but is composed of different kinds of igneous rocks, ranging from granite to diorite. The most noteworthy feature of the entire Coast Range mass of intrusives is their general uniformity in texture and their continuity. The variations across the range are apparently not so gradual as those along its trend. The Coast Range massif consists of many separate interlocking batholiths, or batholiths within batholiths, intruded at successive epochs but during the same general period of irruption.

The petrographic field term "granite," which has been generally used to designate these intrusives, applies to only a small part of the rocks, the prevalent type being a quartz hornblende diorite, though gradations to granodiorite, diorite, and gabbro, with hornblende and biotite as colored constituents and titanite as a frequent visible accessory, are common. As a general rule hornblende appears to be more abundant near the coast, while biotite predominates near the inland border of the Coast Range batholiths.

Although the composition of the batholiths varies considerably from point to point, it is desirable to ascertain the approximate average composition of the entire mass. To this end seven typical specimens were selected from different parts of the range. These specimens were chosen with special regard to their abundance and general distribution throughout the area, abnormal and rare types being disregarded altogether. Each of these specimens was studied in detail under the microscope, and a careful estimate of the relative quantity of each mineral in the rock was made from the thin sections by the Rosiwal method. Although the values thus obtained are only approximate, they represent roughly the general mineral content of the batholiths.

The following average mineral composition was thus obtained:

Average mineral composition of the intrusives of the Coast Range.

Quartz	19.4
Orthoclase	6.6
Andesine ($Ab_{56}An_{44}$)	47.4
Hornblende	7.6
Biotite	11.6
Apatite	.6
Magnetite	.9
Pyrite	.1
Titanite	1.3
Epidote	3.5
Chlorite	.1
Calcite	.1
Kaolin and muscovite	.8
	100.0

The average specific gravity, 2.77, was determined by weighing the hand specimens in air and then in water.

From these data the average chemical composition was calculated by assuming for the hornblende and biotite the compositions of like minerals from a similar rock from Butte, Mont.

Average chemical composition, norm, and classification of the intrusives of the Coast Range.

Average chemical composition.			Norm.				Classification.
Constituent.	Per cent.	Molecular ratio.					
SiO_2	61.0	1.017	Q	16.14	16.14	84.26	Class, $\frac{Sal}{Fem}=4.78$
TiO_2	1.0	.013	Or	13.32	68.12		Order, $\frac{F}{Q}=4.22$
Al_2O_3	17.5	.171	Ab	27.78			Rang, $\frac{K_2O'+Na_2O'}{CaO'}=0.82$
Fe_2O_3	1.6	.010	An	27.02			Subrang, $\frac{K_2O'}{Na_2O'}=0.45$
FeO	2.7	.038	Di	4.81	10.56	15.52	
MnO	.1	.001	Hy	5.75			
MgO	2.4	.060	Mt	2.32	4.29		
CaO	6.9	.123	Il	1.97			
Na_2O	3.3	.053	Ap	.67	.67		
K_2O	2.3	.024					
H_2O	.9	.050					
P_2O_5	.3	.002					
	100.0						

Its chemical and mineral composition places this rock in the family of quartz diorites, of the type tonalite, according to the usual classification. In the quantitative classification of Cross, Iddings, Pirsson, and Washington the rock is dosalic, dosalone, quardofelic, alkalicalcic, and dosodic, and belongs in Class II, order 4 (austrare), rang 3 (tonalase), and subrang 4 (tonalose). In short, it is tonalose of the ordinary type.

The amount of titanite is unusually large, as it is in many of the intrusives of the Coast Range. The hornblende occurs usually in dark prismatic crystals, noticeable for excellent prismatic cleavage and lack of terminal faces. Many biotite flakes are hexagonal and deep brown in transmitted light. A few crystals of apatite are visible to the unaided eye, but this mineral occurs generally in fine hexagonal microscopic crystals. Pale-green veinlets of secondary epidote, which follow fracture planes in the granodiorite, are not rare.

These even-grained rocks generally have the normal, sharply defined, granitoid texture, but include also gradations to holocrystalline porphyritic phases, due to the superior development of the feldspars. Gneissic structure is common near the western margin of the Coast Range belt. In some places gneissic structure has been so far developed in the granite and the neighboring invaded sediments have been so thoroughly converted to gneiss that it is difficult to define the precise limits of the original intrusive granite.

CONTACT FEATURES.

The granite near the contact contains abundant inclusions of the intruded schist. These inclusions become more and more coarsely crystalline away from the contact, until finally they resemble basic or acidic differentiation products and are gradually lost to sight. Pegmatite and aplite dikes form an intricate network and mesh of white strands along the outer portions of the granodiorite massifs and in the adjacent schists, but are practically absent in the central parts of the batholiths. Several systems of such dikes were observed. The oldest set occurs as thin narrow bands following master joint planes and standing out as ribs above the surface of the more easily weathered granite; a second set is wider and usually perpendicular to the first; and a third and still later set, which is distinctly irregular, apparently fills the largest fracture cracks. This condition suggests that during the last period of magmatic activity the rock masses underwent considerable movement and fracturing and were brought nearer the surface. That still later differential movement has taken place is evident from the minor faulting of the pegmatite dikes themselves. At a distance this schist complex, with its innumerable pegmatitic dikes, resembles a breccia, the white pegmatites acting as interstitial cement for the dark angular fragments and blocks of schists. The occurrence of these innumerable pegmatites in the schists along the margin of the Coast Range batholiths is a significant indication of the immense quantities of pneumatolytic solutions given off by the invading crystallizing magmas. However, in this region of most intense development of pegmatites, the amount of ore deposition was slight and no large ore bodies have been discovered.

Farther away from the granitic intrusion magmatic solutions given off by these igneous masses penetrated the schists and encountered conditions more favorable to the precipitation of the metallic sulphides carried in solution and deposited them. As a result the argillites and slates a few miles west of the contact, as on Cleveland Peninsula and Revillagigedo Island, are very heavily impregnated with sulphides, and in certain places the precious metals have been in quantities sufficient to form valuable deposits.

The sedimentary rocks flanking the Coast Range batholiths in this region are folded closely near the contact and more openly at a distance so that, though their general trend is parallel to the range, their dip is extremely variable, ranging from northeasterly to southwesterly at all angles. Within the granite area itself are occasional belts of included sedimentary rocks in a highly metamorphosed condition. They vary from argillites to mica, hornblende, and calcareous schists of various types, even marble, and occur in long bands, intensely folded. They still preserve in general their northwest trend, parallel to the course of the range, and their steep northeasterly dip, and they are walled in by great mountain masses of intrusive granite. Most of the included belts of schist in the Coast Range are not wide, and more appear near the mountain tops than at sea level. They can be traced up the exposed cliffs and bare mountain sides for 4,000 to 6,000 feet. They are in many places intensely mineralized with sulphides, especially pyrite, and near the mountain crests show abundant evidence of contact metamorphism and the formation of garnetiferous rocks.

A comparison of the metamorphic effects of the intrusive granite along its western and eastern flanks in the latitude of the Ketchikan district shows decided differences. On the coastal side the metamorphism near the contact is usually of the deep-seated type; gneisses and schists predominate and are cut by innumerable pegmatite dikes ramifying from the granite. Mineralization by sulphides is not pronounced near the contact. Farther west, at some distance from the contact, evidences of contact metamorphism increase and the degree of mineralization also increases, valuable ore bodies having been discovered within this zone in the Ketchikan district. Along the eastern border of the granite, on the other hand, the metamorphism is of the contact type, and argillites and slates predominate and are in many places indurated and heavily impregnated with sulphides. Well-defined ore bodies have been found near the granite contact. The geologic interpretation of these data indicates clearly that the rocks east of the massifs were less deeply buried at the time of intrusion than those on the coastal side. In other words, the inland rocks were then above the zone of deep-seated metamorphism or rock flowage and were therefore profoundly affected by the invading intrusives and accompanying pneumatolytic solutions. Furthermore, the mineral-bearing solutions emanating from the granite encountered new conditions of temperature and pressure on entering the adjacent sedimentary rocks and deposited, as supersaturated solutions in their new environment, a portion of their dissolved contents, especially the metallic sulphides and silicates.

In this large belt the phenomena of contact metamorphism are not so pronounced and concentrated as in the contact aureole of a small intrusive boss, such as at Copper Mountain. They are equally varied, though more extensive and on a larger scale. It has frequently been observed that in a small contact aureole different contact minerals occur at different distances from the intrusive mass, and that under similar conditions an evident relation exists between a given contact mineral and its distance from the invading rocks; and in a general way this law apparently holds true for this eastern contact zone of mineralized sedimentary rocks.

As further evidence of the important part played by the intrusives of the Coast Range, it may be noted that the ore deposits are apparently all later than these intrusives; that occasionally the pegmatite dikes in this area pass gradually into quartz veins, and that the evidences of contact metamorphism and the development of contact minerals such as staurolite, garnet, and andalusite are not rare in the heavily mineralized rock belts. Nearer the Coast Range the rocks now exposed were at the time of intrusion deeply buried and therefore extremely hot and under considerable pressure. The solutions, escaping from the granite and entering this complex, encountered conditions not greatly unlike those within the crystallizing granite itself, and sulphide deposition was slight. On reaching the zone of less pressure and colder rock formations, however, the ascending solutions met conditions favorable to the precipitation of sulphides and minerals closely allied to those of ordinary contact metamorphism, where heat and magmatic solutions are the prime agents of metamorphism.

OTHER INTRUSIVES.

Dikes of diabase, andesite, porphyry, and felsite are common throughout the region and cut all the older rock strata. Some of these have been indicated on the geologic map. The importance of these rocks, however, is relatively small when compared with the intrusives of the Coast Range and their accompanying dike rocks. For the most part these dikes may be considered as intrusive forms of the greenstones, andesites, and basaltic lavas. Diabase, the most widely distributed dike rock in the region, cuts the ore bodies in many places. It usually has a fine-grained ophitic texture, is dark green, and consists essentially of altered plagioclase feldspar, together with basaltic hornblende largely altered to uralite. Both magnetite and pyrite are generally present in disseminated grains. The porphyries, which may be regarded as the dike rocks of the andesitic lavas, are characterized by their porphyritic texture, by their light-green color, and by large phenocrysts of plagioclase feldspar contained in a finely crystalline groundmass. These dikes are numerous along the shore exposures, where they cut the Paleozoic strata and the granitic intrusives. Narrow dikes of basalt were observed on Kasaan Peninsula and at other localities. They are usually black, finely crystalline, and porphyritic, and vary widely in composition. The basalts are the most recent intrusive rocks.

EXTRUSIVES.

The greenstone extrusives mentioned in the foregoing pages are represented essentially by tuffaceous strata and lava flows, which have been generally metamorphosed and rendered schistose, their original mineral constituents having been replaced to large extent by secondary products. Because of this alteration the former character of the rock has in most places been obliterated, but elsewhere their texture and mineral content mark them as igneous rocks. The interstratification and the intermingling of the igneous material with the black slates indicate that most of the igneous material, composed of tuffs and some agglomerates, resulted from volcanic outbursts. Lava flows also occur, but are less frequent. They are somewhat metamorphosed, have a greenish cast, and range in composition from altered andesites and andesitic tuffs to basalts and altered gabbros.

In their most altered form the greenstone schists are fine grained and are composed largely of chlorite, calcite, and secondary hornblende, which give the rocks a dark-green color. These schists, where permeated by mineral-bearing waters, contain considerable amounts of pyrite, and in several places have been bleached to a light yellow, as on Gravina Island and Cleveland Peninsula.

As is shown on the general geologic map, the greenstones are distributed along the mainland belt including Gravina Island, Cleveland Peninsula, and Duncan Canal and are also well developed along the shores of Hetta Inlet and on Shukwan Island. The greenstones are irregularly involved with the slates, limestones, quartzites, and schists, having been folded and compressed with them, and are considered to be essentially of the same age.

The extrusive rocks provisionally referred to the Jurassic or the Cretaceous are made up of lavas and tuffs like those of the upper Carboniferous. These extrusives include altered andesites, hornblendic porphyries, quartzose porphyries, and basalt tuffs. With these extrusives are included fragmental or clastic rocks composed of volcanic tuffs, sandstones, and conglomerates. As a whole the lavas are less prominent than the clastic rocks. They are intercalated with the sedimentary slates and sandstones or graywackes. The original character and manner of deposition of extrusives must have been very similar to that of the older greenstones. They are, however, readily distinguished from the greenstones by differences in composition and texture and by their dominant reddish color, and also by a difference in the amount of apparent metamorphism of the extrusives. They have not been changed to chlorite or talcose schists and do not show the degree of alteration that is characteristic of the older greenstones. As indicated on the accompanying map, the andesites occupy irregular areas on the south end and along the west coast of Prince of Wales Island but are not known to occur in other portions of the Ketchikan district.

Basaltic lavas of postglacial age occupy small areas at many points along the mainland and on Revillagigedo Island. They lie in nearly horizontal beds on the upturned schists and granitic rocks. The massive lava dominates, but narrow beds of tuffaceous material or ash were also observed. These flows correspond to the lavas on Kruzof Island in the Sitka district to the northwest.

STRUCTURE.

A consideration of the entire coastal province of southeastern Alaska brings out several important features which throw light on the dynamic history of the region. In the Ketchikan district alone these features are not very clearly marked. Prior to the development of the main northwest-trending structural lines, which at present dominate this coastal province and are most pronounced adjacent to the wide areas of intrusive rocks, the prevalent structure was made up of northeastward-trending folds. These folds still form a minor system, prominent on the west coast of Prince of Wales Island. The later and more intense folding of the beds, on a broader scale, which forms the major system and trends northwestward, has in general obliterated this minor system. Nearer the intrusive belts the larger system gradually prevails, and the minor folds as a whole are combined in the broader anticlines and synclines of the major northwest-trending folds. Complex minor folding and fracturing is thus produced in the beds. The fact that beds of upper Carboniferous age have this northeasterly folding indicates that this was the dominant bedrock structure at the close of the Paleozoic era. Whether the younger system of folding was produced just before the intrusion of the granite of the Coast Range or at the time of its invasion has not been definitely established, though, as suggested by Spencer,[1] it was probably before the invasion of these igneous rocks, as the planes of contact, with few exceptions, follow the planes of bedding; to present this structure the strata must have been highly tilted and must have occupied a position similar to that which they now have. Along the mainland, across a width of from 5 to 10 miles, the uniformity of the strike and dip of the stratified rocks adjacent to the Coast Range batholiths indicates a monoclinal structure. Such interpretation, however, would necessitate a still greater thickness of the rock beds at the time of their deposition, as in their present condition they are greatly compressed and metamorphosed. From the evidence of broad folding of the beds it is reasonable to assume that this rock belt has the structure of a closely folded and compressed synclinorium, in which the tops of the anticlines have been removed, leaving little or no definite proof of their existence.

After this great period of mountain building, which is believed to have occurred about the close of Paleozoic or in early Mesozoic time, further important orogenic movements of the earth's crust took place and are clearly shown in the Mesozoic beds on Prince of Wales Island. In certain localities these beds overlie the granite intrusives and have assumed a steeply tilted position, with a northwesterly strike, and are considerably metamorphosed, but at other places they are only slightly folded and show no persistent direction of strike or dip and but little metamorphism. The forces producing this later structure affected the older Paleozoic strata largely by faulting, fissuring, and tilting, and not by intense folding. The structural characteristics in the more recent rock formations indicate tilting and faulting, and there is little or no evidence of folding or metamorphic action. The effects appear to be confined largely to the basins or local areas occupied by these rocks, and in the older beds faults and fissures were probably produced along which the basaltic lavas subsequently found egress.

In addition to the preceding description of the different periods of dynamic revolution, the structurally significant faulting which accompanied these orogenic movements deserves special consideration. Evidence of these faults is shown by the local discontinuity of the strata. These faults, which are possibly numerous, are parallel to the bedding, and are therefore difficult to decipher, because of the extreme metamorphism of most of the rocks.

OUTLINE OF GEOLOGIC HISTORY.

The sedimentary record in this province begins with the deposition of a series of fragmental rocks, now represented by banded quartzite, sandstone, a few beds of conglomerate, and some tuffaceous material. These clastic rocks grade upward into calcareous beds and into limestone containing a Silurian fauna. Though the age of the earliest sediments has not been determined they are believed to be mostly Silurian, as they are succeeded with apparent conformity by limestones of that age. However, since their thickness is estimated at 10,000 feet or more, it is possible that their deposition began in an earlier period. At all events the record shows that sedimentation was probably continuous during early Silurian time, when clastic rocks were deposited to a great thickness, and that there was then a gradual deepening of the sea, and several thousand feet of limestone strata were laid down. The deposition of this Silurian limestone was possibly followed by a period of earth movement, during which the rocks were indurated and more or less folded, but of this fact there is no definite proof.

The oldest representative of the Devonian system is a succession of conglomerate and sandstone beds, composed largely of igneous material, which in most places appear to be less altered than the Silurian limestones and underlying clastic rocks. The pebbles of the conglomerate are embedded in a tuffaceous matrix and were derived chiefly from the older banded quartzite and limestone strata. This series, which is estimated to be 1,200 feet thick, grades upward with apparent conformity into the Lower Devonian limestones. These calcareous beds are nearly 2,000 feet thick and their period of deposition probably extended well up into Middle Devonian time. In other parts of the region the Middle Devonian is represented by argillaceous schists and slaty limestones, but the relations between these and the early Devonian limestones are not known. After deposition of the slaty limestones and argillites and apparently conformable with them a limestone of considerable thickness was laid down in Upper Devonian time. This later limestone, though highly crystalline and in places folded, does not generally show the intensity of dynamic action which characterizes the older limestones.

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[1] Spencer, A. C., The Juneau gold belt, Alaska: U. S. Geol. Survey Bull. 287, p. 14, 1906.

The Carboniferous period seems to have been begun by the deposition of gray limestone beds 1,500 feet or more in thickness, and, though the relations between these beds and the underlying Devonian strata have not been clearly determined, it is probable that a deep sea covered this region from late Devonian to early Carboniferous time. Along the mainland the corresponding limestone beds are infolded with argillites and crystalline schists and are highly metamorphosed. These argillites are, in part at least, Mesozoic. A long period of volcanic activity followed. The beds of lava and ash ejected from the volcanic vents were contemporaneous with the slate beds, and because of their intimate association with the sediments the volcanics are regarded as submarine extrusives. They are now represented by the altered massive greenstones and greenstone schists, which are widely exposed throughout the region and, together with the interstratified slate beds, have a thickness estimated at about 4,000 feet.

The sequence of geologic events during the Mesozoic era is not clearly defined because of the lack of paleontologic and structural evidence and because of the great orogenic changes which took place during this era. During early Mesozoic time the bedded rocks suffered intense metamorphism and recrystallization, resulting in the conversion of the sedimentary strata to schists and slates and in the alterations of the volcanic rocks to amphibole schists and chloritic greenstones. At the same time the beds were highly tilted and intricately folded, the direction of the axes of folding being generally southeast. These changes are exemplified more clearly in the beds flanking the Coast Range than in the sedimentary rocks composing the outer islands. Early Mesozoic slates have been recognized in the Berners Bay district, and, as suggested by Brooks,[1] probably Triassic beds are infolded with these older metamorphosed sediments in the Ketchikan district. The large development of the Triassic deposits to the south in British Columbia points to the same conclusion.

The most important event in this district during Mesozoic time was the intrusion of the great batholiths of the Coast Range. A study of the section across the axial mass of the Coast Range itself shows that the mass is not a simple batholith but is made up of successive intrusions along the same general line of weakness in the earth's crust. On the outlying islands granitic masses, which are much altered and contain many shearing planes, are invaded by granitic intrusives only slightly altered, which in turn are intruded by pegmatitic dikes and masses. Between these successive intrusions considerable time probably elapsed. The main folding and tilting of the bedded rocks referred to above probably preceded the actual invasion of the granodioritic rocks, as suggested by Spencer,[2] a suggestion based on the fact that their lines of intrusion are in a broad way parallel to the bedding planes and schistosity of these older rocks, also on the fact that a few inclusions of schist fragments occur within the intrusive massif. In order to control thus effectively the lines of intrusion of the granodiorites, the invaded sedimentaries must have been highly tilted previous to the time of igneous intrusions.

Observations made in southeastern Alaska and elsewhere show that the geologic processes which combined to produce these vast intrusions and structural phenomena acted very slowly and over long periods of time. Though the Coast Range intrusion is generally considered as having occurred at one period, a conclusion that is undoubtedly true for limited areas, it is probable that in southeastern Alaska, at least, considerable time intervened between the first granite invasion and the final solidification of the last intrusive masses. It is not possible now to refer these granitic intrusions in this province to a definite geologic period, but the evidence available in adjacent provinces indicates that they continued at least until late Middle Jurassic time. These invasions of igneous material were evidently the cause of the vast amount of metamorphism and deformation of the sedimentary strata along their contacts, and it is also probable that many of the ore bodies were deposited just after these igneous invasions, the intrusive containing the material forming the ore. The transfer of igneous material to points nearer the earth's surface naturally produced strains in the earth's crust, which found relief in cracks and fissures and lines of brecciation at the contacts of the intrusives and elsewhere. The lines of weakness thus formed furnished channels that afforded free circulation for mineralizing solutions, which are believed to have been derived for the most part from the igneous masses themselves and to have been given off while the masses were in process of solidification.

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[1] Brooks, A. H., Ketchikan mining district: U. S. Geol. Survey Prof. Paper 1, pp. 22-28, 1902.

[2] Spencer, A. C., op. cit., p. 19.

A period of erosion appears to have followed the intrusion of the Mesozoic granite, and later another epoch of volcanism began. The volcanic rocks of this later epoch are represented by tuffaceous deposits and lavas that occupy considerable areas in the southern and western parts of Prince of Wales Island where they lie on the eroded surface of the granite and are overlain by or interstratified with deposits of plastic rock. The steeply tilted attitude and metamorphosed condition of these volcanic rocks indicate that they were considerably folded but that the structural deformation was not widespread, as it did not greatly modify the early Mesozoic folding which preceded the intrusion of the granite.

The deposition and folding of these Mesozoic strata appear to have been followed by a a long period of quiescence, during which erosion was probably extensive. In upper Eocene time sedimentation took place in local basins. The beds then formed, including fine conglomerate and shales with some lignite, were subsequently tilted and faulted, but this disturbance was apparently local. No evidence of marine life has been found in them and probably they were fresh-water accumulations. They occur only near sea level and in low-lying valleys and basins practically inclosed by mountains of granite and older metamorphosed rocks. These beds represent the most recent sedimentary formations of the Ketchikan district and after their deposition wide areas of land were flooded by basaltic lavas which poured forth through fissures in enormous volume. These lava flows are flat-lying and on Kuiu Island in the Wrangell district attain a thickness of over 1,500 feet. They were probably extruded at the close of the Eocene.

A large part of the Tertiary sediments may have been subsequently removed by erosion, for there must have been a long period of quiescence after their deposition and deformation. The next important event in the region was the development of the ice sheet which covered the entire district. Its retreat left the topography in essentially its present form. After the retreat of the ice some lava sheets were locally erupted.

GENERAL DISTRIBUTION OF MINERALIZATION.

Within the mainland belt and in the eastern part of Revillagigedo Island, in the Ketchikan district, mineralization is scattered both in the granitic intrusives and the adjacent schists, but mineralized zones corresponding to those in the Juneau gold belt to the north are less strongly marked. Quartz veins and metallic impregnations are found only locally, and prospecting has revealed comparatively few valuable ore deposits in the areas occupied by these rocks. Explorations have been confined, however, mainly to the shores of the deep, narrow fiords, from which the mountains rise abruptly to high altitudes. Steep, forest-covered slopes make prospecting difficult and have restricted the knowledge of the greater portion of the schist belt to the vicinity of salt water. The ore bodies thus far disclosed have been developed near Smeaton Bay in Behm Canal; at Sealevel, on the northeast side of Thorne Arm; and near the head of Carroll Inlet. For the most part they consist of simple veins in fissures and lode deposits of complex composition. They contain only moderate values in gold.

In the slate-greenstone belt, which borders Tongass Narrows and includes the western part of Cleveland Peninsula, ore bodies of considerable importance have been formed. They are largely lode deposits or mineralized bands, within which the greenstone schist country rock has been sheared and fissured and then permeated by the mineral-bearing solutions. In these mineralized bands or lode deposits the country rock has a bleached appearance and is impregnated with small cubes of pyrite and other sulphides. Local narrow seams of massive sulphide ore are found and native gold is seen here and there in the vein quartz or appears as thin films or flakes along the jointing cracks and slipping planes. Besides gold and small amounts of silver, copper also occurs in slight amounts in some of the deposits of these rocks.

Though quartz veins are prominent throughout the slate and greenstone belt, some of which show particles of native gold, most of them are too small or their gold content is too low to pay for mining.

On Prince of Wales Island the regularity of the rock structure is locally interrupted by broad, irregular areas of intrusive granitic rocks, and for this reason the ore bodies are not traceable along definite zones. Mineralization is in general closely related to the intrusive rock masses, and many of the deposits are at the contacts of the intrusives or in their vicinity. They occur as large lenticular bodies and as veins of nearly massive sulphide ore composed of pyrite, chalcopyrite, magnetite, and pyrrhotite in a matrix of garnet, quartz, calcite, and other gangue minerals. Such deposits are found on Copper Mountain and on Kasaan Peninsula. Bodies of copper ore inclosed in a greenstone schist country rock, both in lenticular masses and in veins, occur at Niblack Anchorage, at the head of North Arm, and in Hetta Inlet. Bornite and chalcopyrite occur in small patches that are in places disseminated through the granitic intrusives and are being explored on the Goodro claims to the northeast of Karta Bay.

On Prince of Wales Island gold ores are confined principally to the limestones and phyllites and are being mined in the vicinity of Hollis, on Cholmondeley Sound, and at Dolomi. At these points the gold occurs in veins of quartz and in lodes following lines of brecciation in the limestone. It is commonly present in the native form and is in many places accompanied by considerable amounts of silver and copper. The principal ore minerals are pyrite, galena, sphalerite, and tetrahedrite.

Auriferous veins in the granitic intrusives have been located and partly developed on Granite Mountain to the west of Karta Bay, at several points in the vicinity of Shakan, and at Ratz Harbor in Clarence Straits. These veins show that the granitic areas are not everywhere barren of ore, as often assumed.

Ores of silver, lead, and zinc have been observed at several localities on Prince of Wales Island, though the only deposit that has been developed is on the Moonshine claim, in Cholmondeley Sound. At this place the ore occurs in a well-defined vein traversing the limestone and greenstone schist country rock.

COPPER MOUNTAIN AREA.

TOPOGRAPHY.

The Copper Mountain area as here defined embraces about 86 square miles of rugged country on the west side of Prince of Wales Island. (See Pl. II.) It takes its name from Copper Mountain (altitude, 3,946 feet), which marks the center of the area. This mountain and other peaks, such as Mount Jumbo (3,464 feet), Hetta Mountain (2, 961 feet), Billie Mountain (3,250 feet), Green Monster Mountain (2,900 feet), and their connecting ridges and spurs form a rugged highland which is bounded on the west and north by Hetta Inlet (see Pls. III, *A*, and IV, *B*), a deep embayment of Prince of Wales Island. On the east the upland merges into the unmapped mountains of Prince of Wales Island. Hetta Inlet is bounded on the north and west by highlands, only the lower slopes of which have been mapped. Among these is Beaver Mountain, about 3,000 feet in height, occupying the northeast side of the area here considered. Hetta Inlet is for the most part bordered by steep slopes that rise directly from the water or from a narrow rocky beach. Only at the mouths of the larger streams, like Portage, Reynolds, and Hetta creeks, are there any flats, and these are of small extent.

The drainageways are arranged radially, their heads centering around the higher peaks. The valleys have steep slopes and their upper parts have high gradients. Practically none of the valleys exceed 2 miles in length. Lakes are plentiful and occur at many altitudes, occupying basins from 100 to nearly 2,000 feet above sea level. The larger of these are Hetta Lake, in the southern part of the area, and Lake Mellen, Summit Lake, and Lake Josephine, in the central part. These lakes are of glacial origin. The heads of the valleys lie in amphitheater-like basins or glacial cirques, especially those on the northwest slopes of the mountains. Typical glacial cirques occur in Jumbo Basin, at the head of Jumbo Valley (see Pl. III, *A*), and in

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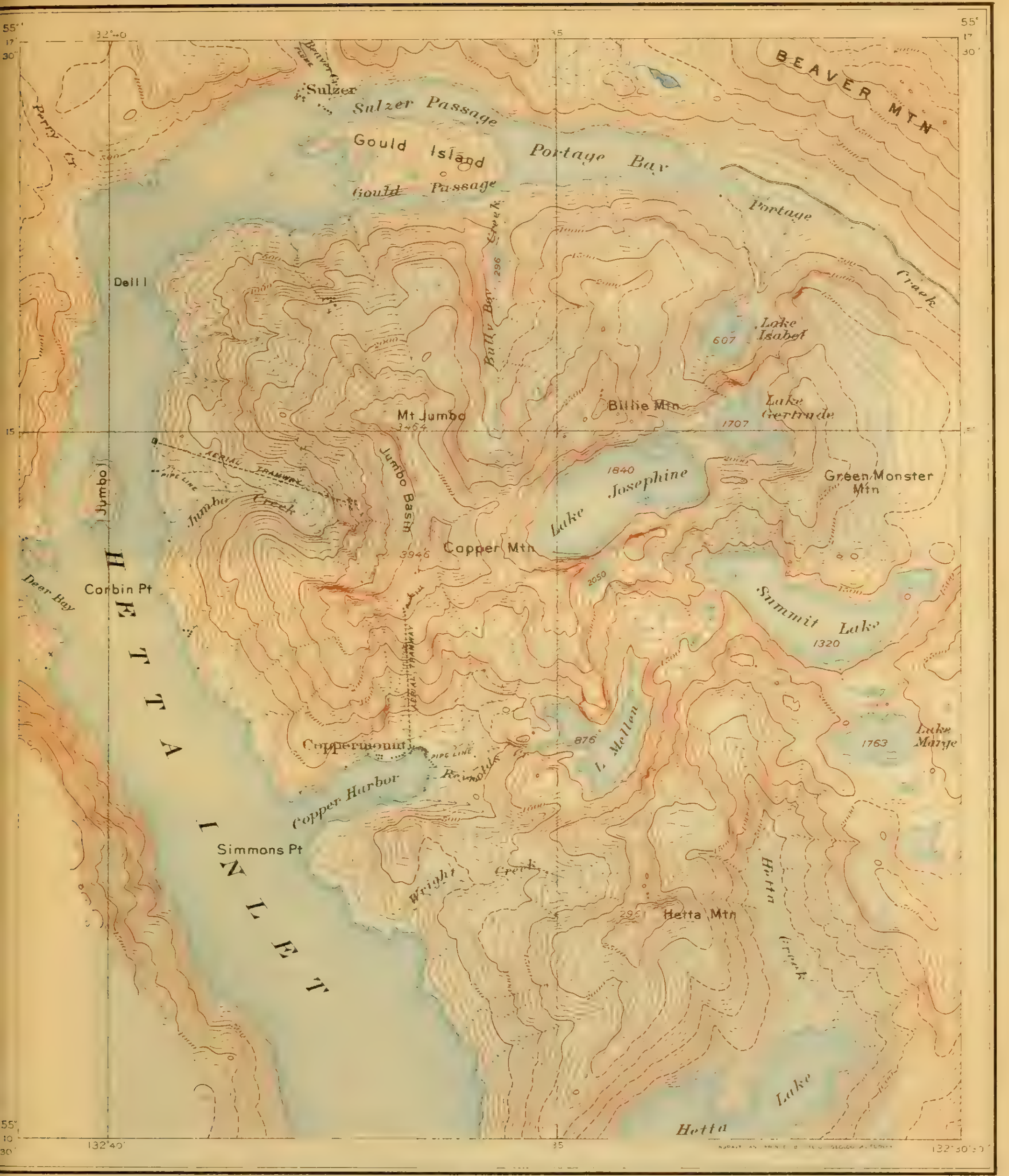
PROFESSIONAL PAPER 87 PLATE II



TOPOGRAPHIC MAP OF COPPER MOUNTAIN AND VICINITY, ALASKA

lfred H Brooks, Geologist in charge of division
opography by R H Sargent
ontrol by Coast and Geodetic Survey
nd R H Sargent
Surveyed in 1908

Scale $\frac{1}{62500}$

1 ½ 0 1 2 Miles

1 ½ 0 1 2 Kilometers

Contour interval 100 feet

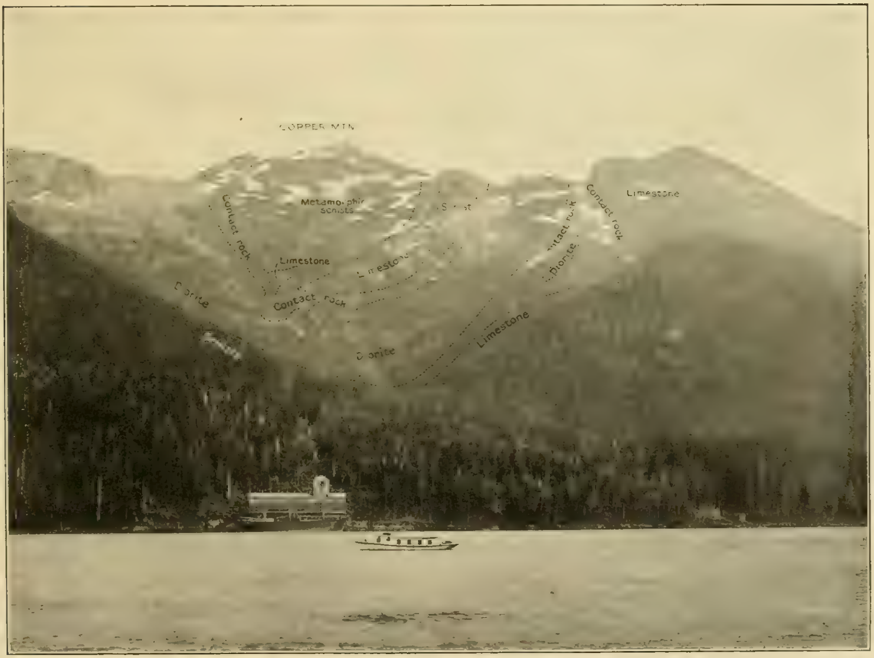
Datum is mean sea level

Dotted lines represent approximate topography

1914

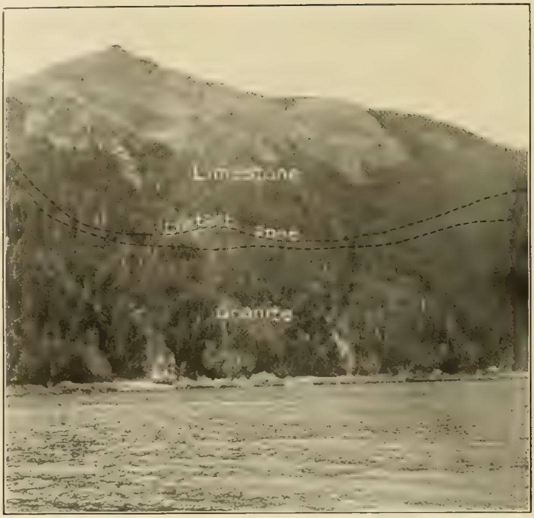
A. VIEW NEAR HEAD OF HETTA INLET.

Showing site of town of Sulzer and the character of the forests.



B. COPPER MOUNTAIN AND JUMBO BASIN.

Showing mine workings and general features of the geology of the mountain. Photograph by Winter & Pond.



A. GREEN MONSTER MOUNTAIN FROM SOUTH SIDE OF SUMMIT LAKE.

Photograph by Winter & Pond.

B. HETTA INLET LOOKING SOUTHWARD FROM COPPER MOUNTAIN.

Copper Harbor in the foreground. Photograph by Winter & Pond.

Hetta Basin, at the head of Wright Creek. The glacial character of the topographic sculpture in the area is further manifested by the occurrence of bowlders and gravel wash in the lower parts of the valleys and by glacial markings on some of the granite knobs.

The mountain slopes are covered with a luxuriant growth of timber and underbrush up to an elevation of 2,000 feet, the timber being useful to the mine operator, though the underbrush renders prospecting difficult. (See Pl. III, *A*.) The mountain lakes form large reservoirs which may furnish a supply of water for use in both mining and smelting.

A broad valley extending eastward from the head of Hetta Inlet and connecting by a low pass with a stream flowing into the head of Cholmondeley Sound furnishes a route of communication between the western and the eastern parts of the island. A wagon road about 4 miles long has been built across this pass.

GEOLOGY.

GENERAL FEATURES.

The general geology and mineral resources of this area have been briefly described in previous reports,[1] but a more detailed statement concerning the geology and ore deposits will be given here. The most striking geologic feature of the area is the irregular granitic intrusive mass that occupies its central part. (See Pl. V.) From this mass spurs or dikes 300 to 600 feet wide diverge into the surrounding series of metamorphic schists and the interstratified beds of limestone. The schists are much wrinkled and sheared and include both calcareous and siliceous varieties, and the limestones are generally marmarized. The rocks nearer the intrusive contact are further altered to a hornfels or amphibolite, which is usually banded with parallel beds containing much garnet and diopside. The principal limestone belt extends from Copper Harbor northwestward into Jumbo Basin, and another belt occurs on Green Monster Mountain (see Pl. IV, *A*) and Hetta Mountain. Narrow bands of schist are interstratified with these limestones, and in turn narrow beds of limestone are interstratified with the schists. Southwest of the main limestone belt on the west slope of Copper Mountain the limestone is overlain by a considerable thickness of altered siliceous schists, which lie conformably on the limestone and grade upward into a succession of amphibole and chlorite schists that are interstratified with quartzites and show no limestone. These chlorite and amphibole schists are interstratified with quartzites, slates, and here and there beds of a massive greenstone that probably represents an ancient lava. They border the east and west shores of Hetta Inlet (see Pl. IV, *B*) and are the most recent bedded rocks in the area.

SEDIMENTARY ROCKS.

The sedimentary rocks within the Copper Mountain area are, as already noted, made up of highly metamorphosed schists and limestones, probably chiefly of Paleozoic age (Carboniferous?). They occupy a steeply tilted position surrounding the granitic intrusive mass. These stratified rocks fall into two divisions—a lower, made up of metamorphic schists and limestones, and an upper, made up of volcanics with some clastics. The distribution of these rocks is indicated on the geologic map. (See Pl. V.)

SCHISTS.

The oldest rocks of the Copper Mountain area are made up of metamorphosed schists composed largely of sedimentary material, though in places they include tuffaceous material and extensive limestone beds. These rocks surround the granitic intrusive masses and are important because of their relations to and influence on the ore deposits.

The schists are for the most part fine grained and crystalline, with amphibole, mica, and quartz as their principal mineral constituents, though in some feldspar, calcite, or chlorite may predominate, and at points near the granitic intrusives they are composed essentially of garnet, epidote, or diopside, with quartz and some magnetite or pyrite. Certain strata consist of carbonaceous, argillaceous schists with local development of graphite; phyllites also occur. Some of the specimens collected resemble a biotite gneiss; they are massive, though much wrinkled, and from the hand specimens their origin is difficult to determine. Calcareous bands occur in these more gneissic schists, and on their weathered surface are projecting ribs of biotite with some quartz.

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[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska, with an introductory sketch of southeastern Alaska: U. S. Geol. Survey Prof. Paper 1, 1902. Brooks, A. H., and others, Report on progress of investigations of mineral resources of Alaska in 1905: U. S. Geol. Survey Bull. 284, 1906; Report on progress of investigations of mineral resources of Alaska in 1906: U. S. Geol. Survey Bull. 314, 1907; Mineral resources of Alaska (report on progress of investigations in 1907): U. S. Geol. Survey Bull. 345, 1908; Mineral resources of Alaska (report on progress of investigations in 1908): U. S. Geol. Survey Bull. 379, 1909.

These rocks are presumably derived for the most part by alteration from argillaceous and calcareous sediments that have been largely crystallized by intense metamorphic action, though some of the schistose strata may represent metamorphosed igneous rocks of volcanic origin.

LIMESTONES.

Thickness and character.—Beds of altered limestone are interstratified with the schists and evidently belong to the same period of deposition. These beds range in thickness from less than 100 feet to more than 1,000 feet. The limestone varies from a white, coarse, crystalline marble to a dark-blue to nearly black, in places finely crystalline to granular though locally thin-bedded and slaty limestone. This change in appearance is due not so much to a change in composition as to a change in alteration or crystallization, this being in part attributable to contact metamorphism caused by the granitic intrusives and in part to regional metamorphism.

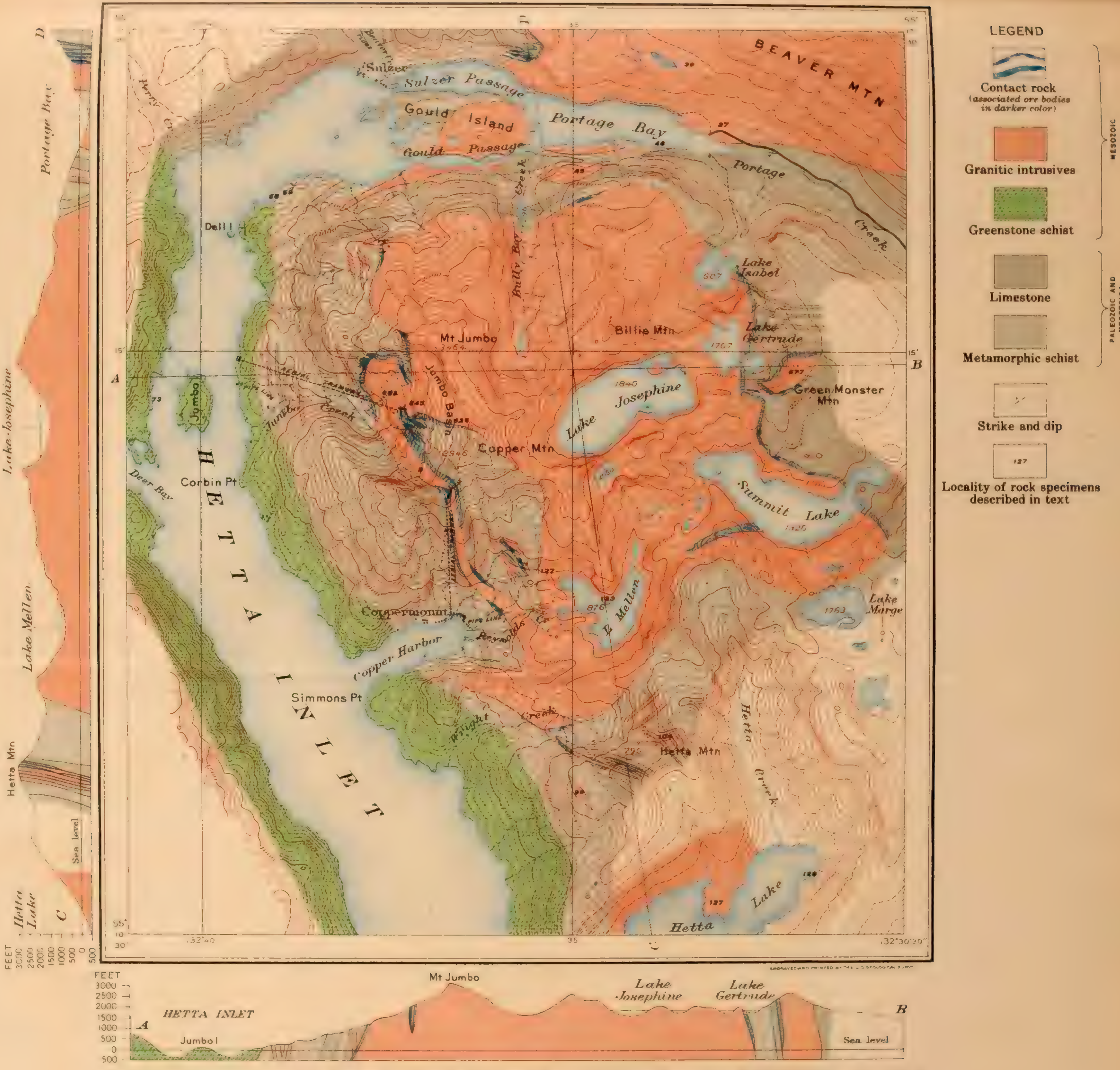
In the hand specimen the crystallized limestone is white with occasional gray patches, granular in texture (average granularity about 1 millimeter), and consists almost entirely of calcite. Under the microscope it appears to be composed almost exclusively of lime carbonate, with rarely a speck of magnetite. The carbonate is evenly granular and intricately twinned.

This rock is the country rock into which the granodiorite of the Jumbo property is intruded and along the narrow margin of which the copper-bearing contact deposits have been formed. An analysis of the limestone from this mine, by George Steiger, is as follows:

Analysis of limestone from Jumbo mine.

SiO_2	0.61
Al_2O_3	.30
Fe_2O_3	.48
MgO	8.00
CaO	46.45
H_2O	.22
CO_2	44.07
S	.06
MnO	.03
	100.22

Occurrence.—These schists and limestones form a nearly continuous belt around the granitic mass which occupies the central portion of the area. In places the limestone members are at the contact, though in general the schists border the intrusive mass. The total thickness of these rocks is difficult to determine because of the folding and compression to which the rocks have been subjected, but it is probably 5,000 feet or more. In Jumbo Basin a wide mass of schist and limestone, which also extends southward over Copper Mountain, is completely surrounded by the intrusive rock. Tongues and small masses of the granitic rock are surrounded by the schists. Near the intrusive contact in the upper part of Jumbo Basin the limestones are marmarized and the schists are silicified or garnetized, whereas lower in the valley, at points away from the contact, the limestone is a blue, finely crystalline rock and the schists are more argillaceous and slaty. On the shore of Hetta Inlet opposite Gould Island and on the mountain slopes the schists and limestones are highly altered and are crosscut by granitic and pegmatitic dikes. They have a general east to northeast trend, approximately parallel to that of the intrusive contact. Some of the strata are mineralized with pyrite and contain also some chalcopyrite. In places they are much wrinkled and resemble gneissoid rocks. On Green



GEOLOGIC MAP AND SECTIONS OF COPPER MOUNTAIN AND VICINITY, ALASKA

By C. W. Wright

Surveyed in 1908 under the direction of Alfred H. Brooks

Scale $\frac{1}{62500}$

1 ½ 0 1 2 Miles

1 ½ 0 1 2 Kilometers

Contour interval 100 feet

Datum is mean sea level

1914

House Doc. ; 63d Cong., 2d Sess.

Monster Mountain and along the ridge just north of it the schists and limestones form narrow interstratified belts, 50 to 500 feet wide, striking in a west to northwest direction, nearly at right angles to the intrusive contact. The limestones are marmarized though somewhat siliceous, and the dominating schist is a brown mica-quartz schist, much wrinkled and containing quartz seams. On the south side of Summit Lake a belt of altered schist about 300 feet wide is included in the granite. This belt strikes southwest and has a nearly vertical dip. It is almost entirely altered to contact rock, its original schistose structure having nearly disappeared, but it shows a distinct banding of the amphiboles and mica, and the adjacent granite includes fragments which may have been derived from the schist.

The basic amphibole schists and the siliceous mica schists both occur on Hetta Mountain and along the southern contact of the intrusive mass, the former on the east slope and the latter on the west slope. The schistosity is nearly at right angles to the intrusive contact and the schists appear to be more compact and show more wrinkling than at the points where they lie parallel with the intrusive contact.

The limestone that forms a belt near Hetta Mountain is a white to bluish crystalline rock and is cut by several granitic dikes.

Age. –These limestones and schists resemble both stratigraphically and petrographically the metamorphic rocks adjacent to the Coast Range batholiths along the seaward side of the mainland. (See p. 16.) The rocks bordering the mainland have been described as the Ketchikan series by Brooks and as the schist band by Spencer. Fossils found in the mainland belt of limestones indicate that they include Carboniferous and probably some Mesozoic strata.

Structure.—Cleavage is usually well developed in the schists where they contain considerable amphibole or mica. The more siliceous beds and those near the contact of granitic intrusives that contain infiltrations of garnet, diopside, or epidote, and also the limestones, do not show this pronounced cleavage but in places show cleavage at right angles to the bedding. It is noteworthy that the lines of schistosity correspond to those of the bedding, a fact that is made evident by the occurrence of the interstratified limestone beds. The stratification of these bedded rocks is indicated at many points on the geologic map by symbols indicating strike and dip. It is clear that the present structure is in large measure due to the influence of the intruded granitic mass. The beds farther south strike northwestward, at right angles to the granite contact, though those on the west and east sides of the granite mass are parallel to the contact both in strike and dip, as are some of those on the north side of the main intrusive mass, where the bedded rocks have an east-west strike and almost vertical dip, and occupy a position between two main granitic masses. (See Pl. VI, *A*.)

Metamorphism.—The alteration of these rocks to crystalline schists is ordinarily attributed to regional metamorphism, which is supposed to have been produced by mountain-building forces operating when the rocks were deeply buried. It is probable that the general metamorphism was effected at an earlier date than that of the granitic intrusion, though a considerable amount of metamorphism may be attributable to the intrusion of the granitic masses. The alterations due to contact metamorphism are considered elsewhere in this report.

GREENSTONE SCHISTS.

Character.—The succeeding strata differ somewhat both in composition and origin, but are principally greenstone schists composed largely of igneous material interbedded with some siliceous sedimentary material. They consist of amphibole and chlorite schists and quartzites. and contain, in places, argillaceous interstratified beds of phyllite and graphitic schists.

The greenstone schists probably represent altered andesite or diabase tuffs and lavas. Their component minerals, most of which are secondary, are in the main amphibole, altered plagioclase feldspar, epidote, chlorite, calcite, quartz, and magnetite. The original plagioclase feldspar is generally altered to zoisite and muscovite and the pyroxenes are changed to amphibole. The microscope shows that the less altered greenstone schists were derived from an igneous rock, probably an augite andesite. The augite, however, is represented by amphibole that occurs in minute needles. The minerals differ in amount in different strata and the rock may be called amphibole schist, actinolite schist, chlorite schist, calcareous schist, or siliceous schist, its designation depending on its mineral composition.

These greenstone schists grade without definite boundaries into a rock composed partly of igneous and partly of sedimentary material, and this in turn grades into a quartzite or a siliceous argillite, composed mainly of sedimentary material. The intercalation of the greenstone schists with the sedimentary beds suggests that they represent extrusives of igneous material thrown out over the sea bottom as volcanic tuff and in some places as a lava bed.

Included quartzite.—The sedimentary beds interstratified with the greenstone schists are indurated, fine-grained to aphanitic rocks, in places showing banded layers, and ranging in color from light gray to dark green. They usually contain pyrite and weather brown on the surface. They do not break easily along the bedding planes but fracture more readily along joint cracks, breaking at right angles to the bedding.

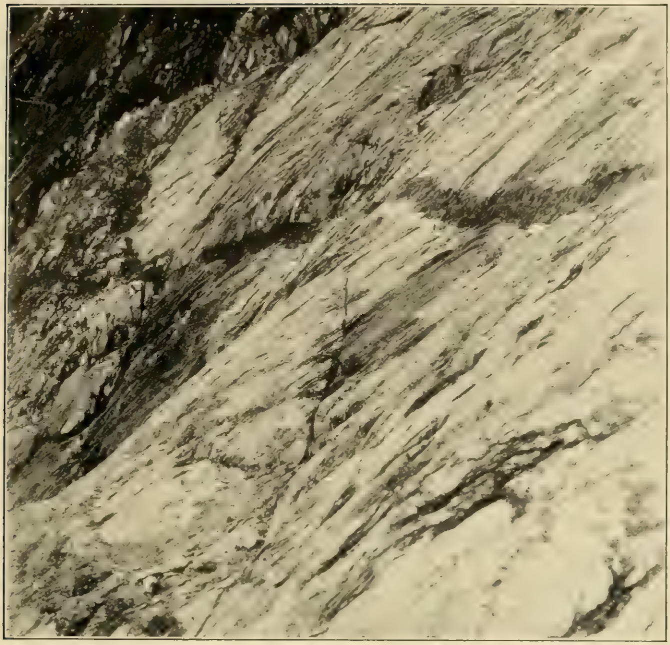
Occurrence.—The greenstone schists border both sides of the main northwest channel of Hetta Inlet, but do not extend along its eastern branch. (See Pl. I.) On the west slope of Copper Mountain they extend to an elevation of about 1,000 feet, where the interstratified greenstone schist members gradually disappear and the quartz-mica schists of the older series are found. No sharp line of demarcation can be drawn between these two formations, and the division is made where the greenstone volcanic material ceases to occur in the stratified rocks.

Near the shore line at the foot of Copper Mountain certain strata of the greenstone schists have a bleached appearance and are of a pale-green color. These rocks contain both pyrite and chalcopyrite as well as quartz stringers and kidneys of quartz and calcite. In places these mineralized strata contain large amounts of copper.

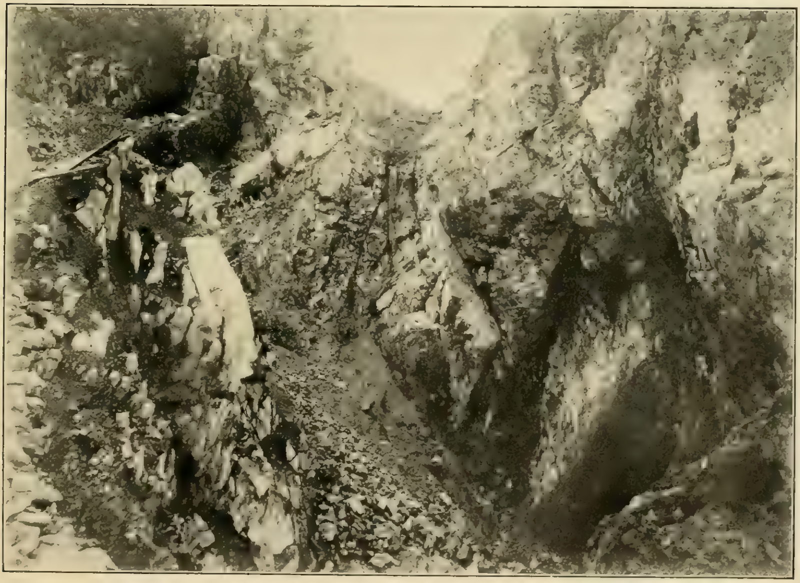
Age.—The greenstones and associated sediments of the Copper Mountain area resemble lithologically the rocks of the mainland belt already described (p. 16). Here, however, the quartzites dominate over the slates. As in the mainland belt, the greenstones are closely associated with limestones that are believed to be of Carboniferous age. In the Copper Mountain region, however, they are clearly younger than the limestones. The slate, graywacke, and greenstone belt of the mainland is in part, at least, Mesozoic, and in the absence of evidence to the contrary it is therefore fair to assume that the greenstones of Copper Mountain are also of Mesozoic age.

Structure.—The structure of the greenstones is much simpler than that of the older schists and limestones. These rocks strike north to northwest and dip NE. 30° to 75°. On the east shore of Hetta Inlet the dip is usually 15° to 30° less than along the west shore. They overlie the metamorphic schists with apparent conformity. They show prominent jointing planes, especially along the west shore of Hetta Inlet, and these strike in general from N. 75° W. to N. 75° E., nearly at right angles to the schistosity, though their dip is almost vertical. Dikes of diabase and basalt, cutting the greenstones and invariably following the direction of the jointing planes, are common.

Metamorphism.—The metamorphism of the greenstones is similar to but less intense than that of the schists and limestones already described. It was doubtless produced by the same forces and during the same periods. The associated sedimentary rocks were originally sandstones, shales, and tuffs, more or less intermixed. The sandstones have been changed to quartzite, the shales to carbonaceous and sericitic schists, and the tuffs to chlorite schists, and just as these originally sedimentary rock beds graded one into the other so do their metamorphic representatives. The metamorphic processes that effected these changes caused a breaking up of the original minerals into secondary minerals, such as the alteration of feldspar to kaolin and sericite and of hornblende and pyroxene to chlorite, serpentine, calcite, and quartz. The combination of these minerals by metamorphism forms other minerals, such as andalusite and staurolite, but such occurrences were rarely noted in the Copper Mountain area.



A. SILICEOUS SCHISTS ON MOUNTAIN SIDE BELOW NEW YORK CLAIM.
Showing basic dike crosscutting the schists. Elevation, 2,500 feet.



B. CONTACT ORE DEPOSIT ON NEW YORK CLAIM, COPPER MOUNTAIN.
Crystalline limestone on right; altered granitic intrusive rock on left.

IGNEOUS ROCKS.

GENERAL FEATURES.

The detailed petrographic and microscopic study of the igneous and contact rocks of this region was kindly undertaken for the writer by Dr. H. E. Merwin, of the Geophysical Laboratory of the Carnegie Institution of Washington. The results of Dr. Merwin's investigations are given in detail in this report.

Coarse-grained massive igneous rocks, occurring as batholiths, occupy nearly half the surface of the Copper Mountain area. Collectively these rocks are commonly called granite, and they have all been mapped in one color under the name of "granitic intrusives." They comprise, however, rocks of several types, which differ widely in composition, and in some places a change in mineral components was noted from part to part of the same mass. These granitic intrusive rocks form the most important geologic feature in the area, principally because the main ore deposits are found at their contacts and were formed at the time of their intrusion. The relations of these intrusives to the ore deposits and the phenomena observed at the contacts are discussed at length in this report.

Other intrusive rocks of minor extent occur within the area in the form of dikes. These dike rocks include granite porphyry, diorite porphyry, pegmatite, aplite, lamprophyre, diabase, and basalt.

GRANITIC INTRUSIVES.

TYPES.

The batholith rock masses in the Copper Mountain area include granitic intrusives of several distinct types, their differences depending largely on the proportions of their component minerals. The factor of greatest influence in determining the rock type is the presence and proportion of orthoclase feldspar. The main type is a diorite, though the proportion of orthoclase may increase in different parts of the same batholithic intrusive mass, and the rock must then be classed as monzonite or, where orthoclase dominates the rock, as syenite. No well-defined lines can be drawn between such variations of the rock type; it is possible to recognize them only by microscopic study of specimens.

These rocks include few true granites, as the proportion of quartz they contain is generally small. A basic type of the granitic intrusives is represented by the gabbros that form some of the smaller batholithic masses. The distinctions between the different rock types are emphasized in the petrographic descriptions.

DIORITE.

The diorite is a coarse to medium grained rock, light to dark gray in color, made up essentially of plagioclase feldspar and hornblende, though in places containing biotite and occasionally pyroxene, as well as small amounts of orthoclase and some quartz, magnetite, titanite, and apatite. The central portions of the diorite batholiths are rather uniform in composition and texture, though near the contact they become less uniform in color and are marked by dark spots, most of which are segregations of hornblende, and in places they are traversed by veins of pegmatite. A type specimen of the diorite (specimen J 4) collected in Jumbo Basin near the mine on Jumbo No. 4 claim, though far enough back from the contact to be free from all secondary alteration, is described below.

The type specimens of diorite were collected principally from Jumbo Basin (specimens 662, 645 to 649) and Beaver Mountain (specimens 39 and 37). They include both hornblende diorite and augite diorite, which in appearance are practically the same as the granodiorite. Rocks of these two types make up the greater part of the granitic intrusives, and it is not possible to define them separately as regards their distribution, as the one evidently grades into the other.

The microscopic petrography of these rocks is described below by Dr. H. E. Merwin.

Specimen J 4: A granitoid rock of medium grain, containing about the following percentages of essential mineral constituents: Quartz, 10; plagioclase, 50; orthoclase, 30; hornblende, 5;

augite, 5; and small amounts of accessory biotite, apatite, titanite, and magnetite. The plagioclase ranges from labradorite to oligoclase, averaging about Ab_2An_1. The central, more calcic zones are altered to epidote.

An analysis of the rock by George Steiger and a calculation of the normative mineral composition is as follows:

Analysis of specimen of diorite from Jumbo Basin.

SiO_2	59.44	TiO_2	0.66
Al_2O_3	17.40	ZrO_2	None.
Fe_2O_3	3.30	CO_2	None.
FeO	2.77	P_2O_5	.28
MgO	1.81	S	.02
CaO	6.51	MnO	.17
Na_2O	4.22	BaO	.07
K_2O	3.12	SrO	.05
H_2O-	.06		
H_2O+	.56		100.44

Mineral composition of specimen of diorite from Jumbo Basin.

Quartz	8.94	Magnetite	4.87
Orthoclase	18.35	Ilmenite	1.37
Albite	35.63	Apatite	.67
Anorthite	19.46	(Water)	.62
Diopside	8.68		
Hypersthene	1.93		100.52

It is evident that the single slide examined did not closely represent the rock analyzed, particularly in respect to the proportion of normative orthoclase and plagioclase. It should be borne in mind, however, that the amount of orthoclase in a rock may be considerably greater than the amount of pure potassium feldspar, on account of the albite which may be held in solid solution. The normative composition places the rock in the group andose.

Specimen 662. Collected from main intrusive mass on trail 500 feet below head of aerial tram, Jumbo Basin.

A granitic rock of medium-grained texture and greenish-gray color. It consists of plagioclase, pyroxene, and biotite, the dark-colored constituents composing 35 to 40 per cent of the rock. In the thin section the plagioclase appears in anhedral grains zoned and twinned. It averages about Ab_2An_1 in composition, ranging from oligoclase to labradorite. The pyroxene is in subhedral grains, nearly colorless except in uralitized areas, where it is greenish. Small grains of plagioclase are included in the pyroxene, which constitutes about 30 per cent of the rock and is essentially augite, but includes some diopside. About 5 per cent of interstitial orthoclase is present. Accessory minerals are biotite, quartz, magnetite, and apatite in relatively large prisms; also titanite.

The rock is an augite diorite.

Specimen 8. Collected from branch of main intrusive mass on south side of Jumbo Basin at an elevation of 2,500 feet.

Both in the hand specimen and in the thin section this rock resembles specimen 662, collected from the main intrusive mass of Jumbo Basin, but it is slightly finer grained and contains zircon.

Specimen 643. Collected from main intrusive mass northeast of head of aerial tram in Jumbo Basin at an altitude of 600 feet.

This rock is medium grained, light gray, and consists of plagioclase and hornblende and small amounts of orthoclase, quartz, pyroxene, and titanite. The plagioclase is zoned andesine, and constitutes 60 per cent of the rock. The hornblende is pleochroic in bright greens and light yellows and some of it contains irregular kernels of diopside. Quartz is a very minor constituent. Orthoclase is abundant, comprising about 20 per cent of the rock. The accessory minerals are biotite, magnetite, apatite, titanite, and zircon.

The rock is a hornblende diorite differing from the preceding in containing much more orthoclase and hornblende instead of augite.

Specimen 39. Collected from intrusive mass of Beaver Mountain north of head of Portage Bay at an elevation of 1,000 feet.

A gray granitic rock of medium grain, showing plagioclase and much hornblende and orthoclase. The slide contains about 40 per cent of zoned oligoclase and labradorite, and 35 per cent of poikilitic hornblende inclosing plagioclase, apatite, magnetite, and kernels of diopside. It is remarkably pleochroic, ranging from bright greenish blue to light yellow-brown and deep brown. It contains 15 per cent of interstitial orthoclase. The accessory minerals, which amount to about 7 per cent, include diopside, biotite, magnetite, titanite, and apatite.

This rock is a hornblende diorite.

Specimen 37. Collected from intrusive mass of Beaver Mountain, at head of Portage Bay.

This diorite is similar in appearance to specimen 39, though it includes larger flakes of biotite and, as seen in the thin section, less hornblende, in place of which it contains from 5 to 10 per cent of diopside and augite. It carries also more orthoclase, containing at least 25 per cent.

GRANODIORITE.

The granodiorite is a medium to coarse grained hypidiomorphic light-gray rock composed essentially of oligoclase feldspar, quartz, orthoclase, and hornblende or biotite. Common accessory minerals are pyroxene, titanite, apatite, and magnetite.

Type specimens of the granodiorite were collected from the main intrusive mass along the shore of Mellen (specimen 133) and Summit lakes and from adjacent batholithic masses on the shore of Hetta Lake (specimen 127) and on Green Monster Mountain (specimen 677). At these localities the rock is practically fresh, showing little or no development of secondary minerals. In composition it is apparently uniform and shows little or no segregation of minerals.

The microscopic petrography of the specimens was studied by Dr. H. E. Merwin and is described below.

Specimen 133. Collected from main intrusive mass at point on north side of Lake Mellen. The hand specimen is medium grained, grayish, and contains well-formed prismatic crystals of hornblende and much plagioclase; also some quartz and orthoclase. Under the microscope the rock shows about 60 per cent plagioclase in subhedral crystals polysynthetically twinned and zoned. The composition of the zones varies from albite to andesine. The hornblende, the other chief constituent, is light yellow to deep green and contains inclusions of plagioclase, titanite, apatite, and magnetite. About 10 per cent each of quartz and orthoclase occurs interstitially. Diopside appears as an accessory; also titanite, magnetite, and apatite.

The rock is a hornblende granodiorite.

Specimen 127. Collected from intrusive mass on north side of Hetta Lake, on the west side of the peninsula.

This rock is decidedly coarse grained, its texture being due in part to the distribution of biotite. Plagioclase, quartz, and orthoclase are the light-colored constituents. Many of the plagioclase crystals are 8 millimeters in length; the biotite scales are 4 millimeters in diameter, and the grains of quartz and orthoclase are somewhat smaller. In the thin section the average of the plagioclase is basic oligoclase or acidic andesine, and the crystals are decidedly zoned. This mineral constitutes about 60 per cent of the rock; quartz, 20 per cent; biotite, 15 per cent; orthoclase, 5 per cent. The accessory minerals are apatite, titanite, and magnetite.

This rock may be classed as a biotite granodiorite, though the specimen examined contains little orthoclase.

Specimen 677. Collected from center of small mass just north of Green Mountain.

A gray medium-grained granitoid rock which in the hand specimen shows as essential constituents plagioclase, orthoclase, quartz, hornblende, pyroxene, and subordinate magnetite and titanite. In the thin section the plagioclase is subhedral and shows pronounced zonal structure, the zones ranging in composition from oligoclase to central cores of labradorite, which are partly altered to epidote. The plagioclase, averaging basic oligoclase, constitutes about

40 per cent of the rock. Orthoclase, with some microcline, is abundant, constituting as much as 25 per cent of the slide studied. Common hornblende and uralite form 10 per cent of the rock; diopsidic augite, 10 per cent; titanite, 2 per cent; and apatite, 1 per cent. Interstitial quartz forms about 10 per cent of the rock.

But for its association this rock might be classed as a monzonite.

SYENITE.

The syenites are medium-grained light-gray to pale-pink rocks composed essentially of orthoclase and plagioclase (oligoclase variety) in different proportions, with hornblende as the principal dark mineral and pyroxene, magnetite, apatite, and titanite as accessories. The type of rock is determined largely by the amount of orthoclase present in the specimen. Where the proportion of orthoclase is much less than that of plagioclase the rock becomes a granodiorite or diorite. In the field it was not possible to recognize these distinctions.

The syenite forms a part of the batholithic masses occurring near its margin (specimens 626 and 121). It is also found in outlying dikes and in tongues branching from the main intrusive masses (specimen 128).

Specimen 626. Collected at point near contact of main granitic mass 1,000 feet east of Jumbo No. 4 mine at an elevation of 3,000 feet.

This is a medium to fine grained granitic rock containing much orthoclase, some pyroxene, plagioclase, and quartz. The visible accessories are pyrite, magnetite, and titanite. Geometric analysis under the microscope shows that the orthoclase constitutes 75 per cent of the mass of the rock. It occurs in subhedral, markedly perthitic crystals, nearly adjacent crystals being separated by a narrow band of quartz and plagioclase. Plagioclase, which composes 5 per cent of the rock, occurs in definitely bounded crystals, some of which form the nuclei of orthoclase crystals. The plagioclase is zoned and twinned according to both the Carlsbad and albite laws. It is essentially albite and oligoclase. The quartz is entirely interstitial and comprises about 10 per cent of the rock. The pyroxene, diopside, which amounts to 8 per cent, is anhedral. Well-formed apatite crystals are both included in and adjacent to the diopside.

The rock is a potash syenite.

Specimen 121. Collected from bluffs in creek just west of Lake Mellen at contact of main intrusive mass.

This is a grayish medium-grained granitoid rock, which in the hand specimen shows orthoclase, plagioclase, and hornblende. In thin section the zoned and subhedral plagioclase was determined to be albite and oligoclase, which constitute perhaps 50 per cent of the rock. The orthoclase is interstitial and amounts to 20 per cent; the hornblende, which occurs in rough prisms, forms 10 to 15 per cent; and the quartz about 5 per cent. The accessory minerals are pyroxene, magnetite, apatite, and titanite.

The rock is a hornblende syenite.

Specimen 128. Collected from dike rock cutting schists on east side of Hetta Lake.

This is a light-gray medium-grained rock of granitic and porphyritic texture. Orthoclase, some plagioclase, and quartz, together with small amounts of hornblende and titanite, are easily distinguished in the hand specimen. Plagioclase (albite and acidic oligoclase) composes about 50 per cent of the rock and occurs in large, regularly bounded crystals. Interstitial orthoclase constitutes 35 per cent of the rock. Quartz grains are plentiful, making up 15 per cent of the rock. Hornblende, diopside, biotite, magnetite, and titanite are the accessory minerals.

This rock is quartz syenite.

GABBRO.

The gabbros are made up of the more basic minerals, largely hornblende and pyroxene with a plagioclase feldspar, usually labradorite, and little or no quartz, and thus the percentage of silica is lower than in the other granitic intrusives. It is difficult in places to distinguish this rock from the diorite, as the two differ mainly in the variety of plagioclase feldspar they contain.

The gabbro constitutes some of the smaller batholithic masses occupying areas adjacent to the main granitic batholith (specimens 45 and 98). Another type of gabbro is found in dikes that cut the sedimentary rocks, but these dikes belong to another period of intrusion and are formed of a coarse phase of porphyrite or diabase. They are described under the heading "Dike rocks," on page 39. Dr. Merwin's petrographic descriptions follow:

Specimen 98. Collected from small intrusive mass three-fourths mile southwest of Hetta Mountain.

This is a dark-gray, coarse-grained rock with large hornblende prisms, grains of pyroxene, plagioclase, and magnetite. The dark crystals compose nearly 70 per cent of the rock. In thin section the hornblende is seen to be poikilitic, including crystals of plagioclase and pyroxene. In certain crystals an inner zone without inclusions has a greenish color. The other minerals are zonal plagioclase (labradorite), which compose 15 per cent of the rock; interstitial orthoclase, forming 7 per cent; and greenish pyroxene, slightly uralitized, forming 10 per cent. Accessories are magnetite, apatite, titanite, and some biotite.

The rock is a hornblende gabbro.

Specimen 45. Collected from intrusive mass on the south side of Portage Bay at an elevation of 500 feet.

A dark-gray, medium-grained rock containing long crystals of hornblende, which form the greater part of it, the remainder consisting of labradorite (20 per cent) and pyroxene (10 per cent). The accessory minerals are magnetite, apatite, titanite, and biotite.

The rock is a hornblende gabbro.

DISTRIBUTION OF THE IGNEOUS ROCKS.

The granitic intrusives constitute the core of the mountain mass that occupied the center of the area indicated on the map as composed of igneous intrusives. There is no evidence that this batholithic mass represents more than one period of intrusion, for it is uniform in character throughout, though the composition of the rock of which it is formed is variable. In the main Copper Mountain and Beaver Mountain masses at some distance from the contact the prevailing rock is uniform in grain and color and ranges in composition from granodiorite to diorite. Near the contact orthoclase occurs locally in amounts sufficiently large to make the rock a syenite. Representative specimens of the syenite were collected at a point one-half mile west of the summit of Copper Mountain, near the border of the Copper Mountain mass (specimen 626). The granodiorite, as is shown by specimens 127 and 133, forms the shore lines of Hetta Lake, Lake Mellen, and Summit Lake. On the west slope of Jumbo Basin, between Copper Mountain and Mount Jumbo, the diorite dominates (see specimens 643 and 662) and forms steep cliffs, locally called the Palisades, which show columnar structure due to jointing planes. The rocks of these cliffs are noteworthy, as the dark constituent of the diorite in their upper part is principally augite, whereas near the contact it is principally hornblende. The huge blocks of diorite that have fallen from these cliffs would make good building stone.

STRUCTURAL FEATURES.

The main structural features of the granitic intrusives observed on the surface exposures are shown on the areal geologic map, and their probable underground extensions are shown on geologic cross sections. The structural relation of the intruded rocks to the intrusives has already been mentioned. No pronounced structural breaks occur within the granitic intrusive masses. The joint planes follow two principal directions—northwest and northeast—and have deeply inclined to vertical dips. Near the borders of some of the masses are fractures filled with later intrusive dike rocks or quartz-feldspar veinlets. Faults of structural importance were not observed.

The joint planes and fractures near the borders of the batholithic masses are generally supposed to have been produced by forces developed when the magma was cooling.

The underground form or limit of the batholithic mass is shown by the attitude of its contact surfaces, which, except at a few places, dip under the intruded rocks at an angle of

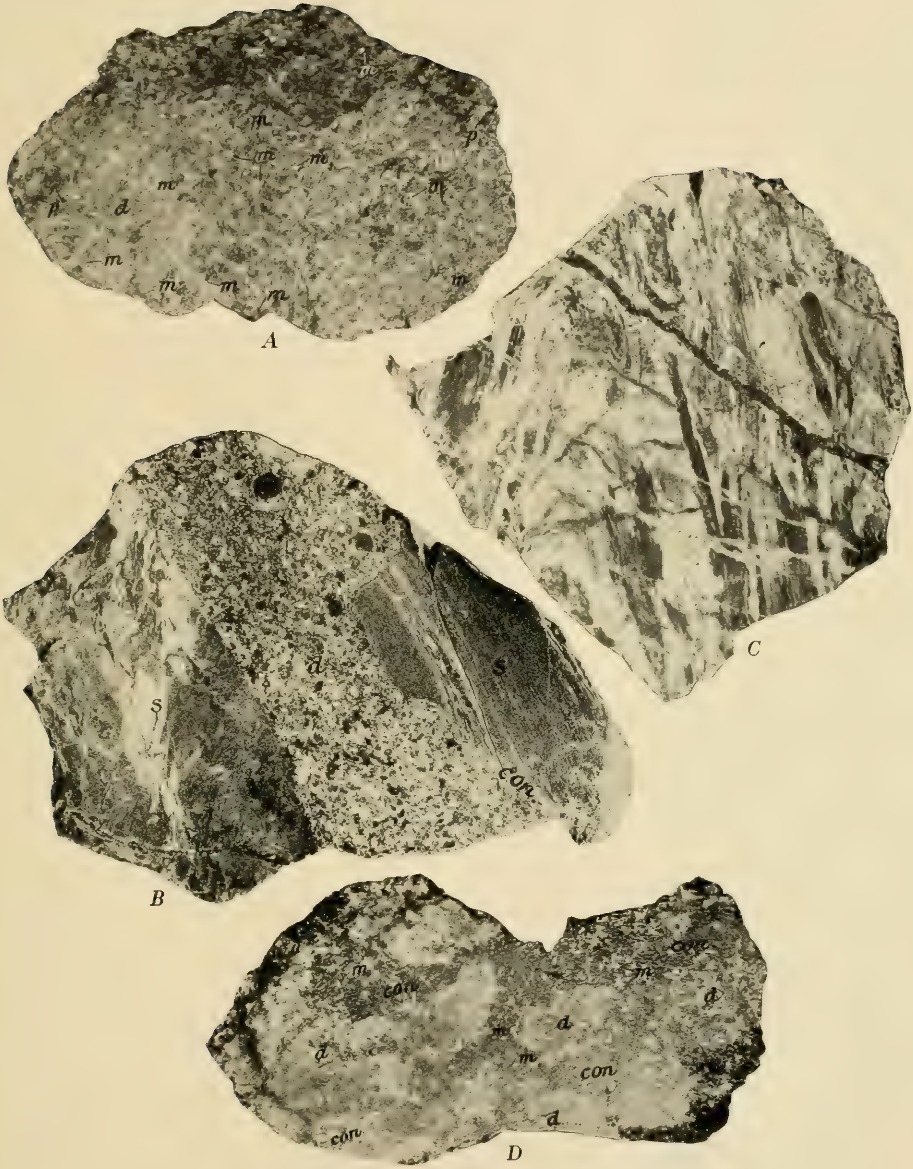
PLATE VII.

A. Altered diorite from the contact zone on Jumbo claim No. 4. The granitic texture is partly preserved though the feldspars are altered to scapolite and the amphiboles to diopside. Throughout the rock are small reflecting flakes of molybdenite, which are represented on the plate by the small white specks. *d*, Altered diorite; *m*, molybdenite; *p*, pyrite.

B. Fragment of schist from Jumbo claim No. 1, containing abundant pyrite, pyrrhotite, and magnetite. Such fragments of various sizes are included in a hornblende diorite. Many of the fragments are bordered by narrow rims (0.5 millimeter wide), which appear to be due to alteration by the diorite. *d*, Diorite; *s*, metamorphosed schist; *con*, contact of included schist, poorly defined, owing to partial absorption by igneous rock.

C. Metamorphosed schist adjacent to granite contact, which has been fractured and interstices filled with feldspar, quartz, and garnet. Specimen from Jumbo claim No. 1. The dark schistose bands contain plagioclase, quartz, and biotite. The dark vein contains diopside and plagioclase. The light patches are plagioclase with some quartz.

D. Altered diorite from contact zone on Jumbo claim No. 4. This specimen shows the diorite more altered than in *A*. Only patches of the granitic rock are preserved, surrounded by the contact rock, which is made up essentially of diopside and calcite with scattered grains of chalcopyrite. *d*, Altered diorite; *m*, molybdenite; *con*, contact rock containing scattered grains of chalcopyrite.



ROCKS FROM ZONE OF CONTACT OF SCHISTS AND DIORITE IN COPPER MOUNTAIN AREA.

about 70°. The relation of the intruded and intruding rocks is well exposed in many gulches that traverse the contact, the granitic rock forming the bed of the gulch and schist or limestone forming the banks. The structure of the intruded rock beds apparently had little influence on or control of the intrusion of the main masses, for the intrusion evidently determined the present position of the bedded rocks. The larger dimensions of most of the smaller granitic masses, however, lie in the bedding planes of the stratified rocks.

MARGINAL PHENOMENA.

The margins of the granitic intrusives show various noteworthy phenomena. The margin of the main granitic mass is in places irregular, forming deep bays, whereas at other points it forms nearly straight lines. Wide areas of the intruded schists are included within the intrusive mass and tongues of the intrusives branch out into the schists. At the margin of the intrusives there are many included fragments of the intruded rock of various sizes, ranging from minute pieces to masses several feet in diameter, and parts of some of these appear to be replaced by minerals that compose the intrusive. (See Pl. VII.) No faulting occurs at the margin of the intrusive or intruded rock and only small disconnected displacements in the rocks were noted. The intruded schistose beds are usually bent to conform with the contact of the intrusive masses, though in places they are much crinkled and squeezed or even brecciated. In general, however, it may be assumed that the intrusion of the granitic rocks took place at depths below the zone of faulting and fracturing, where the rocks were under pressure so great that they were very flexible. At certain points, however, a good example being in the lower tunnels on Jumbo No. 2 claim, the main intrusive mass has penetrated an area of brecciated schists, filling the interstices between the fragments and partly replacing them. Such phenomena are not uncommon at the contacts of most of the intrusive masses in southeastern Alaska. A change in the composition of the intrusive rock at points adjacent to ore-bearing zones is characteristic of the Copper Mountain area. Near the immediate contacts of the intrusive mass at these places diopside and orthoclase are the dominant mineral components, and scapolite or wollastonite occurs in abundance between the intrusives and the contact rock.

AGE.

It is evident that the granitic intrusives are more recent than the greenstones, which are the most recent bedded rocks in the Copper Mountain area. The intrusion therefore probably occurred in Mesozoic time. These granitic masses are similar in composition and character to those of the main Coast Range belt and were perhaps intruded during the same period of igneous invasion. Their age therefore is probably late Jurassic or early Cretaceous.

DIKE ROCKS.

PEGMATITES AND APLITES.

Dike rocks composed essentially of alkali, feldspar, and quartz occur in the neighborhood of the large granitic masses. Some of these rocks are coarse grained, containing large crystals of feldspar, and are classed as pegmatites; others are fine grained and rather uniform in texture and are classed as aplites. Together they form in places a network of small dikes and stringers within a zone of fractured schists, though they are more prominent as separate dikes traversing the granitic intrusives. The rock in some dikes appears to be composed essentially of quartz with very little feldspar and epidote and some garnet, and also magnetite and pyrite. These dike rocks are readily recognized by their light color, granular texture, and mode of occurrence.

The modes of formation of the aplites and pegmatites associated with the batholithic intrusives have been discussed by many geologists, and the intimate relation in origin between these dikes and the quartz veins and ore deposits has been pointed out by Spurr,[1] Lindgren,[2] and Barrell.[3] The general belief is that the pegmatite dikes at least are produced by aqueo-igneous activity, through a process intermediate between injection of molten magma and precipitation from aqueous solutions.

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[1] Spurr, J. E., Geology of the Yukon gold district, Alaska: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 3, p. 311, 1898.

[2] Lindgren, Waldemar, The character and genesis of certain contact deposits: Am. Inst. Min. Eng. Trans., vol. 31, pp. 242-244, 1902.

[3] Barrell, Joseph, Geology of the Marysville mining district, Montana: U. S. Geol. Survey Prof. Paper 57, 1907.

The intimate association of the aplite and pegmatite dikes with the deposits in the contact zones and their relations to the ore deposits and the granitic intrusives are considered more fully under the heading "Genesis of the ores" (p. 102). The microscopic petrography of a specimen of the rock is described by Dr. H. E. Merwin as follows:

Specimen 622. Collected from a point on trail to Jumbo mine at an elevation of 700 feet. This rock is fine grained, almost white, and contains about 45 per cent each of orthoclase and plagioclase. The plagioclase varies in composition from Ab_4An_1 to Ab_2An_1. The rest of the rock mass is made up of 8 per cent of quartz and 2 per cent of hornblende, zircon, and other minerals. The rock, then, is an adamellite aplite.

PYROXENE-FELDSPAR DIKES.

Dikes or veins of rocks composed essentially of pyroxene and feldspar occur within the contact zones and branch out into the intrusive and intruded rocks. These rocks vary widely in composition, ranging from those containing 90 per cent of feldspar and 10 per cent of pyroxene to those containing 70 per cent of pyroxene and 30 per cent of feldspar. In some of them garnet and sulphide minerals occur both as primary mineral constituents and in cracks or veinlets as secondary minerals. The rocks have a medium to fine grained granular texture and are usually light to dark green in color, though where orthoclase dominates they are flesh-colored. These rocks cut the granitic intrusive rocks and were probably injected into fissures in the contact zone in a manner similar to the aplite dikes though at a somewhat later period. Their intersection by veinlets of garnet and the alteration of the feldspars in some of them to scapolite indicate that their formation antedates that of the ore deposits, though they may have been formed at about the same time, and their composition suggests that they were derived from the same underlying magma that produced the contact rock.

The microscopic petrography of the rock is described by Dr. H. E. Merwin as follows:

Specimen 11. Collected from 10-foot dike in contact zone one-half mile southwest of Copper Mountain at an elevation of 2,500 feet.

This rock occurs in small dikes or veins which are confined to the borders of the intrusive masses and cut both the intrusive rock and the contact rock. It also occurs in irregular masses at the margins of the granitic intrusives.

The rock is of fine-grained granitic texture, flesh-colored, and in the hand specimen shows patches of light-green pyroxene in a groundmass made up of irregular grains and plates of orthoclase. Under the microscope orthoclase and diopside are shown to be the chief constituents; albite, titanite, and apatite are present as accessories and compose about 1 per cent of the rock mass. The orthoclase constitutes about 90 per cent of the rock, and occurs in both anhedral grains and in subhedral plates showing Carlsbad twinning. The pyroxene is subhedral and is colorless to pale green. Optically, it is diopside with a probable slight mixture of ægirite in the greenish grains. Its distribution is somewhat irregular. This rock may be called a diopside orthoclasite.

An analysis of the rock made by Chase Palmer and calculations from the analysis by the methods of the quantitative system show the following chemical and mineralogic (normative) composition:

Chemical composition of diopside orthoclasite.

SiO_2	62.03	K_2O	12.38
Al_2O_3	16.39	H_2O	.24
Fe_2O_3	.72	H_2O+	.61
FeO	.86	TiO_2	.53
MgO	1.60	P_2O_5	.13
CaO	3.60		
Na_2O	1.08		100.17

Mineral composition of diopside orthoclasite.

Quartz	1.26
Orthoclase	73.39
Albite	9.43
Anorthite	3.06
Diopside	8.89
Wollastonite	1.04
Magnetite	0.93
Apatite	.34
Ilmenite	1.06
(Water)	.85
	100.25

The notable characteristics of the rock are its high orthoclase and low quartz. The normative orthoclase is higher than for any rock in Washington's tables,[1] and the actual orthoclase (which includes the normative albite and anorthite in solid solution) is higher still. A quartz-orthoclasite listed on page 143 of Washington's tables contain about the same amount of normative orthoclase. The rock belongs in the rang nordmarkare of the quantitative system, but its high potash content places it in a hitherto unrepresented subrang—the perpotassic—which may properly be called hettose, from the occurrence of the rock on the shores of Hetta Inlet.

Specimen 615. Collected from 6-foot dike cutting diorite in long tunnel 500 feet from mouth of New York claim.

This is a greenish holocrystalline rock consisting of a light-colored pyroxene (about 70 per cent) and plagioclase feldspar which is largely altered to scapolite. Much of the scapolite is in individual crystals more than a hundred times as large as the feldspar crystals replaced, giving the rock a poikilitic appearance. Euhedral crystals of pyrite and much chalcopyrite and pyrrhotite are scattered through the rock. The last two minerals appear to have been introduced at the same time as garnet and epidote, which fill many joints in the rock. What appears to have been an earlier set of minute veins filled with feldspar are now parts of scapolite crystals. The pyroxene occurs mostly in small rounded grains, but also in larger, irregular crystals. This mineral is unaltered.

Specimen 623. Collected from 4-foot dike cutting diorite and contact rock just below open cut on New York claim.

A fine-grained rock which in the hand specimen is greenish with irregular bright pink blotches. Under the microscope the green color is found to be due to a pyroxene which occurs in rounded grains and irregular crystals having a very fresh appearance. The pink masses are altered feldspar. Phenocrysts of acid labradorite have been altered to very fine grained aggregates. The alteration has extended around the phenocrysts into the plagioclase of the groundmass, thus making the pink areas irregular. The predominant mineral of the aggregates, though not occurring in grains large enough for positive identification, is probably a light-colored mica. In the slide it resembles the scapolite of other altered rocks of the district, but it has positive elongation parallel to the cleavage. Examined in powdered form, its refractive indices were found to be 1.56 to 1.59. Other minerals in the alteration aggregates are calcite and a mineral having moderate to weak double refraction and refractive index of about 1.69 –probably zoisite.

Specimen 658. Collected from dike on Jumbo No. 4 claim, upper surface workings.

A fine-grained granitic rock containing about 50 per cent each of basic plagioclase and a pale-green pyroxene. The minerals are very fresh, even where cut by numerous veins of garnet. A few grains of the pyroxene are altered to a more highly refracting mineral showing interference colors like zoisite. This alteration seems to have taken place before the garnet veins came in. These are sharply bounded by fracture surfaces.

PORPHYRIES.

Porphyritic dike rocks are common within the area and were observed principally along the shores and in the streams that traverse the schists and limestones (probably largely Carboniferous) as well as the later greenstones. They cut the granitic intrusives and the aplite dikes and are therefore of more recent intrusion. The porphyritic dikes are generally 5 to 50 feet wide but average about 12 feet in width. The rock consists of a finely crystalline groundmass with phenocrysts of basic plagioclase and hornblende.

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[1] Washington, H. S., Chemical analyses of igneous rocks published from 1884 to 1900, with a critical discussion of the character and use of analyses: U. S. Geol. Survey Prof. Paper 14, 1903.

The microscopic petrography of the rock is described by Dr. H. E. Merwin as follows:

Specimen 59. Collected from south shore of Hetta Inlet 1 mile west of Gould Island.

This is a light greenish-gray fine-grained porphyritic rock containing phenocrysts of plagioclase. In the thin section the plagioclase (acidic andesine) forms 75 per cent of the rock, a light-green slightly pleochroic hornblende, in irregular crystals and scattered grains, forms 15 to 20 per cent, and magnetite forms 5 to 10 per cent. Titanite, epidote, and calcite occur in very small amounts. The groundmass shows a decided parallel arrangement of the plagioclase crystals due to flow structure.

The rock is a diorite porphyry.

Specimen 104. Collected from a dike 30 feet wide near the ore deposit on a ridge on the west slope of Hetta Mountain.

This is a medium to fine grained porphyritic rock containing abundant plagioclase and scattered phenocrysts of hornblende. Under the microscope the phenocrysts of plagioclase, approximately andesine in formation, appear to be well-bounded crystals, zoned and twinned. The hornblende occurs in ragged prisms, shows pleochroism from light yellow to light green, and is partly chloritized. The groundmass is made up of a finely granular plagioclase that exhibits no distinct twinning or zoning but shows undular extinction. Magnetite, titanite, and apatite are accessory constituents.

The rock is a porphyry.

Specimen 73. Collected from dike 6 feet wide cutting schists on the west shore of Hetta Inlet opposite Jumbo Island.

This is a fine-grained porphyritic rock with long, slender phenocrysts of hornblende up to 2 centimeters in length, having a parallel arrangement, probably due to flowage in the magma before crystallization. Many of these crystals show effects of magmatic corrosion. The hornblende, which constitutes 35 per cent of the rock, is pleochroic, ranging from light yellow to dark yellow-green. A colorless pyroxene occurs in irregular grains in small amount—about 3 per cent. The feldspar (andesine to acidic labradorite) occurs in very small poikilitic crystals which are usually not twinned. Alteration to chlorite and calcite has begun. The feldspar, including a plagioclase of similar composition in the groundmass, constitutes 45 per cent of the rock mass. Magnetite is abundant, forming about 10 per cent of the rock.

The rock is a diorite porphyry or lamprophyre.

LAMPROPHYRE.

Dikes of lamprophyre, most of them 1 foot to 6 feet wide, cut the rocks near the granitic contacts. (See Pl. VI, *B*, p. 32.) They are generally much altered and in places are faulted, and no older intrusive rock was noted in the area. They are older than the ore deposits or the granitic intrusives. The dikes in the contact zone are broken and have been here and there much altered and in part replaced by minerals of the contact rock. The rock is black, fine grained, and of porphyritic texture, and contains phenocrysts of pyroxene, mostly uralitized. Plagioclase and uralite compose the groundmass. The accessory minerals are magnetite and titanite.

Dr. Merwin describes the microscopic structure of the rock as follows:

Specimen 651. Collected from open cut in gulch on Jumbo No. 4 claim, Copper Mountain.

This rock is greenish black, of aphanitic texture, and under the microscope shows about 70 per cent of amphibole, 20 per cent of altered plagioclase, 5 per cent of biotite, and some pyrite, titanite, and magnetite. It is traversed by veinlets that vary from mere threads to ribbons several inches wide, formed of garnet and diopside. The rock near these veinlets and at the contacts has assumed a lighter color, owing to the bleaching of the hornblende.

The rock is an altered lamprophyre.

Specimen 658. Collected from dike cutting limestone at mine workings in gulch on Jumbo No. 4 claim.

A fine-grained to porphyritic greenish-black rock containing altered labradorite (60 per cent) showing zonal structure. The groundmass contains also chlorite and magnetite and secondary veinlets of diopside and garnet. Near the contacts of the dike and adjacent to the veinlets the rock is altered to a lighter green.

The rock is an altered lamprophyre.

DIABASE.

Many dikes of diabase were noted along the shores of Hetta Inlet. They cut the greenstones and here and there the older schists and limestones. They are generally from 2 to 10 feet wide, and most of them strike northeastward across the stratification of the country rock. The diabase is essentially a plagioclase-augite rock of diabasic texture, dark-green color, and medium fine grain. In certain places coarse-grained dikes of this rock, the largest 50 feet wide, resemble gabbro, though they still retain a diabasic texture.

These diabase dikes are evidently younger than the granitic intrusives and the ore deposits, for they cut the contact deposits on the Green Monster claim, as well as those in the greenstone schists on the Corbin claim. They have no genetic relation to the ore deposits.

Dr. Merwin's descriptions follow.

Specimen 58. Collected from point 1½ miles north of Jumbo Landing, on east side of Hetta Inlet.

The rock is of porphyritic texture. Large crystals having the outlines of augite form the phenocrysts. This augite and that appearing in the groundmass are entirely uralitized. Feldspar occurs in small crystals. Very many slender prisms of apatite, included by the feldspar, and minute crystals of titanite are the principal accessory minerals. The rock contains 70 per cent of uralite, 25 per cent of labradorite, and 5 per cent of accessory minerals.

The rock is an altered diabase.

Specimen 48. Collected from 15-foot dike cutting schists on south shore of Hetta Inlet, 1 mile east of Gould Island.

This rock is medium to fine grained and of porphyritic texture. The phenocrysts are 4 to 7 millimeters in length and consist of plagioclase and hornblende. The plagioclase (acidic labradorite) is twinned after the Carlsbad and albite laws and makes up about half the volume of the rock. So much feldspar is inclosed on the irregular margins of the hornblende crystals as to give them a poikilitic appearance. The biotite, which constitutes about 5 per cent of the rock, occurs in very fine scales, scattered rather evenly. Magnetite and pyrite occur in small grains in the groundmass.

The rock is a diabase or, more specifically, a hornblende dolerite.

GEOLOGIC HISTORY.

The record of the periods of sedimentary deposition and igneous intrusion represented in the Copper Mountain area is defined only by structural relations, not by paleontologic evidence. The oldest sedimentary strata are the schists and limestones, which are probably largely of Carboniferous age, an inference based on their marked similarity to the metamorphic schists of the mainland belt, where included limestone beds contain Carboniferous fossils, though they probably include some strata of Mesozoic age. This metamorphic series is made up of a great thickness of bedded rocks, originally argillaceous, calcareous, and siliceous shales and sandstones, and may include several conformable formations. More recent in age are the greenstones, which overlie the schists and limestones with apparent conformity. They are characterized by their content of volcanic material, indicating an extensive period of volcanic eruption, which assumed the form of tuffaceous outbursts rather than that of lava flows. Evidence from adjacent areas indicates that these rocks were deposited in Mesozoic time. Later all these bedded rocks were subjected to mountain-building forces, which induced metamorphism and upturned the stratified rocks within the area. During this period basaltic dikes or lamprophyres were injected along fracture planes in the rocks and were also subjected to faulting and flexuring due to the mountain-building forces.

The most important geologic event in the region was the granitic intrusion, which continued during a long period and by which a large quantity of igneous material was carried from an underlying magma into the overlying sedimentary rocks. The main granitic intrusion is regarded as Mesozoic, probably late Jurassic or early Cretaceous, and conforms in age to the Coast Range intrusions. The intrusion of the granitic masses was followed by the injection of pegmatite and aplite dikes, which are regarded as differentiation products of the granitic magmas.

The next important event was the deposition of ores at the contacts of the intrusive masses—an event that closely followed the injection of the pegmatite and aplite dikes. The ore deposits were accompanied by large masses of garnet-epidote-diopside rock, which, like the ore deposits, are believed to have been derived from the underlying granitic magma. The most recent rocks in the area are the porphyritic and basalt dikes, which are fairly abundant. These intrusions probably occurred in Mesozoic time. The record of the more recent geologic periods, though not found in the rock formations, is represented in the present topographic features, which have already been described.

COPPER ORES OF THE COPPER MOUNTAIN AREA.

GENERAL CHARACTER.

The Copper Mountain area presents exceptional opportunities for a study of the relations between the igneous intrusives, the ore deposits, and the occurrence of minerals attributable to metamorphic actions, but as only a few months were spent in the field, and as an exhaustive study of the minerals and rock specimens collected has not been made, the problems presented can be only briefly considered.

In order not to confuse observed facts with hypotheses regarding ore genesis, metamorphism, and like phenomena, only the observed facts will be stated here and the more theoretical questions will be discussed under the heading "Genesis of the ores" (p. 102). The principal metal in all the ore deposits in the area is copper, gold and silver appearing in minor quantities. Considerable bodies of magnetite are associated with some of the copper ores, but these have not yet been mined except for their copper content. Zinc and lead are present in some of the ores but not in commercial amounts. The deposits consist mostly of primary minerals, the ores not having been enriched by the action of surface waters.

GEOGRAPHIC AND GEOLOGIC DISTRIBUTION.

The distribution of the ore deposits is clearly shown on the geologic map of the Copper Mountain area (Pl. V, p. 30). This map indicates the location of ore bodies on which some development work has been done and which are described under the heading "Mining in the Copper Mountain area" (p. 53).

The relation of these deposits to the geology, and especially to the granitic intrusives, is best seen by reference to the map. A striking fact is that most of the deposits are at the contacts of the granitic intrusives with the limestones and schists, especially in the places where the line of contact forms strong reentrants. Other deposits occur in the greenstones at a considerable distance from the intrusive contacts.

TYPES OF ORE DEPOSITS.

The following three types of ore deposits have been recognized in the Copper Mountain area:

Contact deposits, occurring at the contact of the granitic rocks and the schists and limestones; containing chalcopyrite associated with pyrite and magnetite or pyrrhotite in a gangue of garnet, pyroxene, amphibole, epidote, and other metamorphic minerals; also calcite and some quartz.

Vein deposits, occupying fissures or shear zones in the greenstones and containing shoots of massive sulphide ore composed of chalcopyrite and pyrite, with some sphalerite, in a quartz-calcite and chlorite gangue.

Disseminated deposits, consisting of mineralized schistose beds in the older schists. Chalcopyrite and pyrite are finely disseminated through these beds and are accompanied by quartz and calcite veinlets.

The contact deposits are the most important commercially and of greatest interest geologically and are therefore considered at length in this report. The vein deposits are less important, though at two mines they have been developed to a considerable extent. The disseminated deposits are at present of little importance and have been only slightly developed, for their low metal content prevents their exploitation.

CONTACT DEPOSITS.

THE CONTACT ZONE.

The contact deposits occur within the contact rock that occupies a zone surrounding the granitic intrusive masses. This contact rock is made up of various combinations of minerals, its principal components being garnet, amphibole, pyroxene, epidote, and calcite, which occur together in separate crystalline groups or more often as a felsite-like mass. The contact rock occurs irregularly around the contact zone; in some places it is entirely lacking and in others it has a surface width of several hundred feet. Its surface width at many points is much greater than its actual width, especially on hillsides where the dip of the intrusive rock surface is only slightly steeper than the slope. Its usual width, however, ranges from 25 to 250 feet. At certain localities the intrusive and intruded rocks are in direct contact with each other, the minerals composing the contact rock being notably absent.

In some places dikes or veins of the contact rock branch out into the limestones and schists and occupy fissures in the granitic intrusive. Few of these veins are more than 1,000 feet long. Large areas of the contact rock occur just within the granitic intrusive and on the surface appear to be surrounded by the granitic rock. These areas may represent wide fractures within the intrusive which have been filled with the contact rock, or they may be masses of the intruded rocks which have been replaced by the contact rock.

THE ORE IN THE CONTACT ZONE.

Types of contact deposits.—The ore within the contact zone occurs in irregular masses that range in diameter from 10 to 100 feet. These masses generally occur on one or the other side of the contact zone; they are rarely found in the center.

The contact deposits may be divided into two classes, according to their mineral composition. In certain deposits chalcopyrite ore is associated with masses of magnetite and these are distinguished as the chalcopyrite-magnetite type. In other deposits chalcopyrite is associated with pyrrhotite and these are distinguished as the chalcopyrite-pyrrhotite type.

Chalcopyrite-magnetite type.—The chalcopyrite in deposits of the chalcopyrite-magnetite type is usually disseminated and seldom in rich masses. The gangue minerals are garnet, amphibole, and pyroxene, and the deposits are compact and finely crystallized. Deposits of this type were noted only between the granitic intrusive and the contact rock, as on the north side of Jumbo Basin, where erosion has removed the overlying contact rock and the magnetite deposit exposed resembles a shell or coating on the surface of the granitic intrusive. This deposit is from 5 to 15 feet thick and over 100 feet wide. At its contact with the granitic rock, which is the footwall, the ore, with the contact minerals, grades into the intrusive mass, the minerals of which are replaced by garnet, epidote, calcite, etc. This zone of gradual replacement between the contact rock and the intrusive is often many feet wide. On the hanging-wall side is the contact rock, which is overlain by metamorphic schists, and here also there is no line of demarcation between the two rocks but a gradual change due to replacement of the schists by the contact minerals.

Chalcopyrite-pyrrhotite type.—In this type chalcopyrite and pyrrhotite, the two principal sulphide minerals, occur associated together and also in separate masses. The gangue minerals are garnet, diopside, epidote, calcite, and rarely quartz. (See Pl. VIII.) Pyrite is present but no magnetite. As a rule these minerals are coarsely crystallized, calcite filling the interstices and small crystal druses being common. These features of crystal occurrence are more clearly evident in rock adjacent to the ore bodies and help to indicate the location of the masses of sulphide ore. Farther away from the ore bodies the contact rock is more compact and even felsitic in aspect. These features of the ore deposits are clearly shown in the mine tunnels on Jumbo No. 4 claim at the head of Jumbo Basin. Deposits of the chalcopyrite-pyrrhotite type are most likely to be found where limestone occurs at the contact or on the contact rock adjacent to the limestone. They are also found at the contacts of the granitic rocks with the contact rock and in masses of contact rock that lie within the granitic intrusives. One of the most important masses lies within a vein of contact rock that branches out into the limestone beds, away from the contact zone.

Relation of intruded rocks to contact deposits.—The influence of the different rock strata at the contacts of the intrusive masses on the nature of the contact deposits is noteworthy, as the character of the intruded strata determines to some extent the location of the ore masses. However, these rock beds have not entered into nor do they determine in large measure the composition of the contact rock which incloses the deposits, as has been pointed out in reports on other districts where contact deposits occur. Where limestone forms the wall rock the effect has been to limit the ore deposits and the contact rock rather abruptly; in other words, the minerals of the contact deposits do not penetrate the limestone wall. The limestones at these points show no bedding planes, are very pure in composition, are recrystallized to a fine white marble, and were apparently impervious to the mineralizing solutions. Large rounded detached masses of the limestone walls occur within the contact rock, and the edges of these masses and those of the limestone walls indicate that this rock has been dissolved or eaten away by the mineral solutions that deposited the ores and the contact rock. As many of the richer ore masses occur where the limestone is present, the limestone may have assisted in precipitating the sulphide minerals. This question is discussed under the heading "Genesis of the ores" (p. 102).

Where the schistose rocks form the walls of the contact deposits the mineralization is less concentrated, the contact rock shows less tendency to crystallize, and the minerals show less tendency to segregate. The sulphide ores are more disseminated in the contact rock, and the contact minerals, including the sulphides, penetrate the schists for some distance from the contact. Angular fragments of the schistose rocks are in places included in the contact rock, and veins of the latter extend along fissures and between the schist strata for some distance away from the contact zone. The schists that show this replacement by the minerals composing the contact rock are essentially calcareous, whereas the more siliceous rocks apparently suffered little change during the mineralization.

Location of minable ore.—The productive ore masses found in the contact zone are confined chiefly to Jumbo Basin and the Copper Mountain ridge just above Jumbo Basin. (See Pl. III, *B*, p. 28.) These deposits are of the chalcopyrite-pyrrhotite type. Large deposits of the chalcopyrite-magnetite type occur on the north side of the Jumbo Basin and are said to contain sufficient copper to make them minable, but they are far away from transportation lines.

Other ore masses have been prospected at many points around the granitic intrusive masses, but most of them are not convenient to lines of transportation and it has been difficult to do development work on them, so that on most of the locations little has been done but the annual assessment work.

VEIN DEPOSITS.

Most of the vein deposits are in the schists, with which they generally coincide in strike and dip. These veins are persistent in length and depth, and the ore in them occurs in shoots of massive sulphides, essentially chalcopyrite, pyrite, and some sphalerite, associated with calcite, quartz, and chlorite. These shoots are 1 foot to 4 feet wide, 20 to 80 feet long, and at one locality have been developed to a depth of more than 100 feet. Those parts of the veins that carry no ore are well marked by gouge containing pyrite and veinlets of quartz and calcite.

The altered schist near the veins is pale green to white, the color of the rock grading away from the veins into the general dark-green color of the unaltered schist. Veins of this type have been developed at the Corbin and Red Wing mines, both situated near sea level along the east shore of Hetta Inlet. These deposits will be described in detail under the heading "Mining in the Copper Mountain area" (p. 53).

DISSEMINATED DEPOSITS.

At a few points in the Copper Mountain area mineralized schists carrying small amounts of copper and gold have been found, and on certain of these deposits small developments have been made. Some of these deposits extend for long distances and range in width from 5 to 25 feet. They are intercalated in the older schists and some of them are more or less fissured, the fissures carrying quartz and calcite. The principal deposits of this type occur in the lower part of Jumbo Basin at an elevation of about 300 feet. Because of their low copper content they have not been extensively explored and have not yet become productive.

MINERALS OF THE DEPOSITS.[1]

SCOPE OF THE DISCUSSION.

The minerals composing the ore deposits in the Copper Mountain area are doubtless of less interest to the miner than the ore bodies themselves, but the mineralogy of the ores is important to the geologist and may assist him materially in determining the conditions under which the deposits were formed. Here, however, only brief mention will be made of the ore and gangue minerals of the deposits. Detailed descriptions of the essential features of each mineral may be found in any textbook on mineralogy. The primary ore minerals are described first, then the secondary ore minerals, and then the gangue minerals and other minerals in the contact zones.

PRIMARY ORE MINERALS.

Chalcopyrite.—The principal ore in the Copper Mountain district is chalcopyrite, the sulphide of copper and iron, which occurs in the contact deposits chiefly in masses more or less mixed with pyrite and pyrrhotite (see Pl. VIII, *E*), in the vein deposits in rich though relatively small ore shoots, and in the disseminated deposits in finely scattered particles, generally not in amount sufficient to form an ore. Chalcopyrite is readily distinguished from the iron-sulphide minerals by its brass-yellow color and by the fact that it is softer and powders readily under the knife blade. In the contact deposits it is associated with pyrite, hematite, and, more rarely, molybdenite, the gangue minerals being principally garnet, quartz, calcite, pyroxene, amphibole, and epidote; in the vein deposits it is accompanied by sphalerite or galena. At the Jumbo mine chalcopyrite and garnet fill spaces between interlacing crystals of scapolite. In the contact deposits chalcopyrite is in places well crystallized in druses, though in the other deposits no crystals were observed. The other sulphides of copper—namely, bornite and chalcocite—were not noted in the district.

Pyrite.—Pyrite, a sulphide of iron, occurs in all the ore deposits and is scattered through the metamorphic rocks of the region and finely disseminated in the igneous rocks. It has not been found in masses large enough to make it valuable as an ore of sulphur. The copper ores contain large percentages of pyrite, which carries gold in amounts ranging from $1 to $2 to the ton. The pyrite disseminated in the schists also contains gold.

Pyrrhotite.—The occurrence of pyrrhotite is similar to that of pyrite, though it is less widely distributed. It is a sulphide of iron containing less sulphur than pyrite and is readily distinguished by its darker bronzelike color and its magnetic properties. It occurs in large masses in the contact deposits, but was not noted in the vein deposits. (See Pl. VIII.)

Pyrrhotite ores containing sufficient nickel to make a nickel ore occur at Sudbury, Canada, and at several foreign localities, notably at Kongsberg, Norway. Because of this association

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[1] The writer is indebted to Dr. H. E. Merwin, of the Geophysical Laboratory of the Carnegie Institution of Washington, for a detailed study of the minerals collected from this region. The results of Dr. Merwin's investigations are given in the mineral descriptions.

PLATE VIII.

A. Ore containing irregular groups of pyrite crystals and chalcopyrite in a gangue of calcite, diopside, and garnet. Specimen taken near granite contact, Jumbo claim No. 4. *c*, Calcite; *ch*, chalcopyrite; *dc*, diopside, calcite; *g*, essentially garnet; *p*, pyrite.

B. Scapolite. This mineral occurs in masses of radiating crystals in druses. Specimen from upper workings on Jumbo claim No. 4.

C. Specimen showing contact of limestone with contact rock. At the contact and adjacent to it in the limestone a very light colored amphibole has been developed. The main mass of dark rock is diopside and calcite, but in the immediate vicinity of the ore and to a less degree in other parts of the mass a dark amphibole appears. The limestone is rather pure. *c*, Calcite; *ch*, chalcopyrite; *ag*, calcite amphibolite, garnet; *dg*, diopside, garnet.

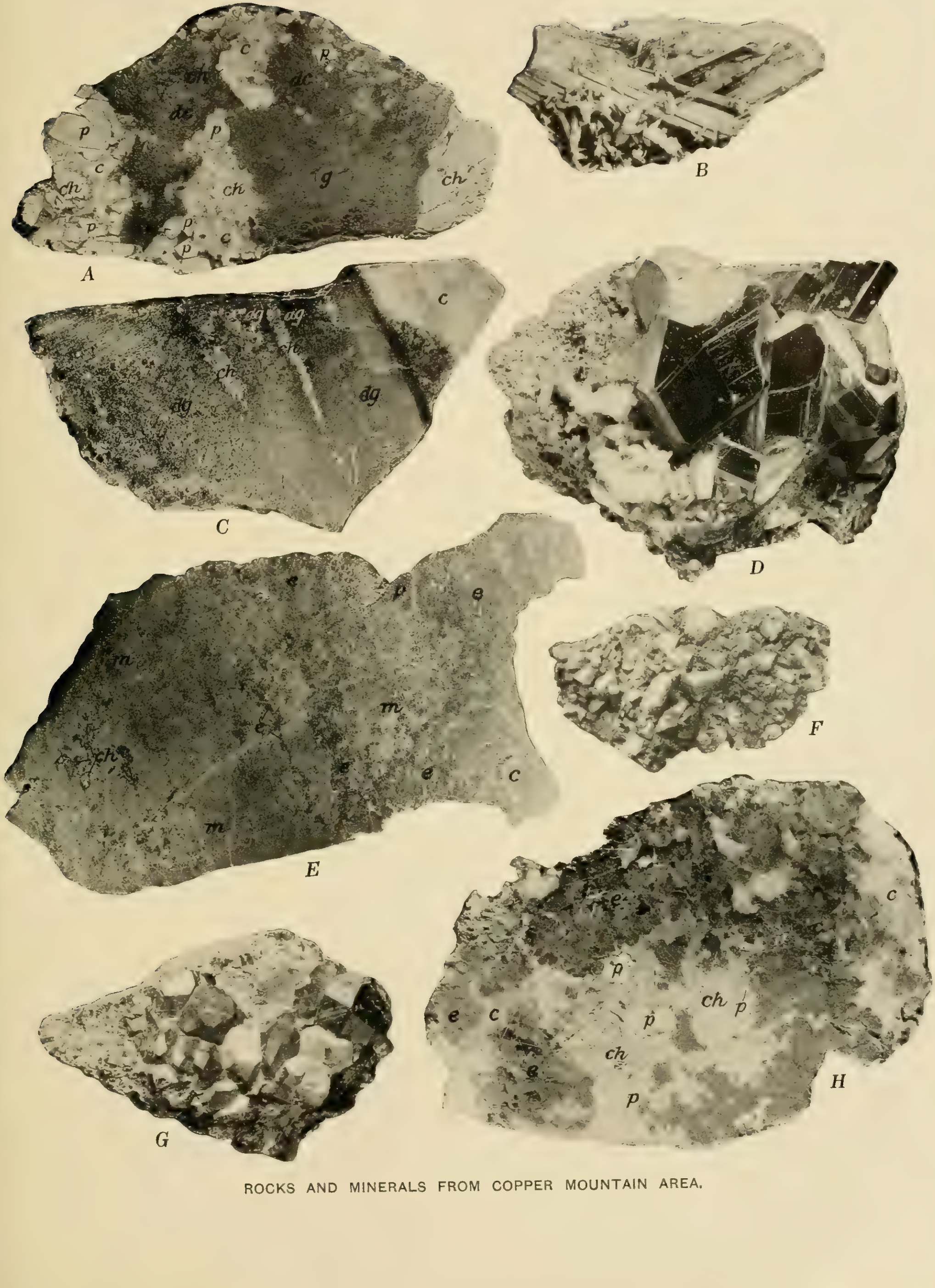
D. Group of epidote crystals and cluster of quartz crystals on contact rock. Specimen from west slope of Green Monster Mountain near summit.

E. Metallic minerals (magnetite, pyrite, and chalcopyrite) associated with minerals of the contact rock, principally epidote and calcite. Specimen from Jumbo claim No. 1. *c*, Calcite; *ch*, chalcopyrite; *e*, epidote; *m*, magnetite; *p*, pyrite.

F. Adularia showing prismatic crystals with slightly curved faces. Specimen from north side of Green Monster Mountain near summit.

G. Garnet. These crystals are smaller and of a more uniform color than the garnet which predominates in the contact deposits. From New York claim, Copper Mountain group.

H. Crystals of pyrite inclosed in pyrrhotite. The gangue consists almost entirely of calcite, which is tinged greenish in places by inclusions of minute diopside crystals. From Jumbo claim No. 4 near limestone contact. *c*, Calcite; *ch*, chalcopyrite; *e*, epidote; *p*, pyrite.



ROCKS AND MINERALS FROM COPPER MOUNTAIN AREA.

and because masses of this mineral at one locality were reported to contain large amounts of cobalt, samples of nearly pure pyrrhotite were taken at two different localities and submitted for determination of their content of nickel, cobalt, platinum, and gold, with the following results:

Assays for rare metals in pyrrhotite ore.

[Assays made by George Steiger, United States Geological Survey.]

	Nickel.	Cobalt.	Platinum.	Gold.
	Per cent.			
No. 5. Sultana claim, north side of Hetta Inlet, Ketchikan district, Alaska	0.1–0.2	Trace.	None.	None.
No. 6. Iron-Crown claim, Copper Mountain, Ketchikan district, Alaska	.1– .2	Trace.	None.	None.

Sphalerite.—The mineral commonly called zinc blende, the sulphide of zinc (sphalerite), containing 67 per cent zinc, having generally a dark color and a semimetallic luster and distinguished by its light-brown powder, is found in the vein deposits associated with chalcopyrite and galena, quartz and calcite being the gangue minerals. It is not known to occur in quantities sufficiently large to make a zinc ore.

Galena.—Galena, the sulphide of lead, occurs in small amounts in vein deposits on Gould Island, associated with chalcopyrite and sphalerite, with calcite and quartz as gangue minerals.

Molybdenite.—The rare mineral molybdenite, the sulphide of molybdenum, occurs in the contact deposits, usually in small flakes in the contact rock or in the altered granitic rock near these deposits. At the Jumbo No. 4 claim it is associated with garnet, calcite, diopside, and chalcopyrite. It is a soft, flaky mineral with metallic luster resembling graphite but having a bluer tinge. It is not found in the Copper Mountain region in commercial quantities. (See Pl. VII, *A*.)

Magnetite.—Magnetite, the magnetic oxide of iron, occurs in large masses at the intrusive contacts, associated with the copper ores. Such masses are common in Jumbo Basin, where they have been largely developed. (See Pl. VIII, *E*.)

Minute grains and octahedral crystals of magnetite occur with the ferromagnesian silicates and in the groundmass of the greenstone schists and some of the intrusive rocks. Magnetite was also observed in certain pegmatite or aplite dikes and in quartz veins, with calcite, pyrite, and chalcopyrite.

The presence of chalcopyrite in these magnetite masses makes them important copper-bearing deposits and their high iron content gives them value to the smelters as a flux in the reduction of copper.

The occurrence of the magnetite in association with chalcopyrite, pyrrhotite, and pyrite in the contact deposits shows that it was deposited under conditions similar to those under which these sulphides were formed. In the intrusives, on the other hand, magnetite is apparently an original constituent.

Specularite.—Nearly all the contact deposits contain small amounts of specularite or micaceous hematite, an anhydrous oxide of iron. Its association indicates that it was deposited at the same time as the copper ores and under similar conditions. Flat crystals of specularite one-half inch across, showing numerous rhombohedral faces around the edges, were found.

SECONDARY ORE MINERALS.

Limonite.—The hydrous oxide of iron, limonite, is found principally at the surface outcrops of the ore deposits, having been formed largely from the decomposition of the iron sulphides. It occurs principally in association with the copper carbonate ores on the Copper Mountain ridge, where it extends to a considerable depth below the surface. In general these oxidized or secondary ores form only a shallow capping on the sulphide ore deposits.

Malachite.—The green mineral malachite, the basic carbonate of copper, is found in small amounts at the outcrops of the copper deposits, usually where limestone forms the inclosing rock. It occurs principally in small masses in a garnetiferous and limestone gangue on Copper Mountain, where surface alteration has been extensive. It generally forms narrow seams or veinlets and incrustation or coating on the sulphide ores and is associated with limonite, chrysocolla, and small amounts of cuprite. Its high copper content and the facility with which it may be smelted make it a most desirable copper ore, but no large deposits of it have been found in the district.

Azurite.—Azurite, like malachite, is a carbonate of copper, but may be distinguished by its deep-blue color. It was observed in small amounts only and invariably in association with malachite as a surficial alteration product of the sulphide copper ores.

Chrysocolla.—The hydrous silicate of copper, chrysocolla, like malachite and azurite, has been found in notable quantities only at the Copper Mountain mine, where it is apparently confined to the surface workings and is of minor importance.

Cuprite.—Cuprite, a red oxide of copper resulting from the oxidation of the sulphide ores, occurs in small amounts at the surface workings of the Copper Mountain mine.

Copper.—Native copper was observed at the Jumbo Basin mines on Copper Mountain and at the Houghton group. It occurs as thin flakes in cracks or gouge seams at the outcrops of the ore deposits. It is probably the result of deoxidation of cuprite and is therefore secondary.

GANGUE MINERALS.

Garnet.—Garnet is the principal gangue mineral of the contact deposits and is confined chiefly to the intrusive contacts. Though it commonly occurs in massive form, resembling a felsitic rock, it appears also in crystal aggregates associated with epidote, quartz, and other silicates. (See Pl. VIII, *G.*) The garnet found is mostly of the variety andradite, but includes some grossularite. The separate crystals are principally dodecahedrons with trapezohedral faces slightly developed. In cross section they show concentric structure resembling banded agate, being made up of yellow to pale-green and red bands which represent slight changes in composition occurring during the growth of the crystals. Partings parallel to the dodecahedral faces between zones of different colors indicate an interruption in growth, and some of the partings contain thin layers of calcite. (See Pl. VIII, *G.*) The crystals range in size from a few millimeters to 5 centimeters and many of them are twinned. In color the garnets differ greatly, presenting several shades of green, yellow, and brown. The crystal faces show subadamantine luster, though the masses have a rather greasy luster. To determine the variety of this massive garnet samples were submitted for analysis. The results of these analyses and of analyses of garnet from other localities are presented in the following table:

Analyses of garnet occurring in contact deposits.

	1	2	3	4	5	6
SiO_2	35.18	36.26	37.79	37.15	35.5	40.0
Al_2O_3	5.15	.78	11.97	6.98		22.7
Fe_2O_3	25.05	32.43	15.77	19.40	31.5	
FeO	.40	.32	1.31			
MgO	.09	None.	.37			
CaO	33.36	29.67	32.57	32.44	33	37.3
H_2O	.42	.57	.09			
TiO_2	None.	None.				
$CaCO_3$		None.		4.20		
P_2O_5		.06				
MnO		.27	.31			
	99.65	99.67	100.18	100.60	100	100

1. Garnet rock, Jumbo mine, Prince of Wales Island, Alaska. Analyst, W. T. Schaller.
2. Garnet, Morenci, Ariz., U. S. Geol. Survey Prof. Paper 43, p. 134. Analyst, George Steiger.
3. Massive brown garnet, White Knob, Idaho, Econ. Geology, vol. 2, No. 1, p. 7.
4. Garnet, San Jose, Mexico., Am. Inst. Min. Eng. Trans., vol. 36, p. 92.
5. Typical composition of andradite.
6. Typical composition of grossularite.

The above analyses show that the larger percentage of the garnet associated with contact deposits is andradite and not grossularite.

The masses of garnet are confined principally to the contacts of limestone of nearly pure calcium carbonate, with igneous rocks, suggesting that a vast amount of foreign material has been introduced along the intrusive contacts. Where the intrusives invade a quartzite country rock the garnet forms bands in the siliceous beds, many of the bands extending thousands of feet from the contact. At Copper Mountain the garnet forms a massive belt, 25 to 150 feet wide, between the intrusive diorite and the limestone country rock and occurs in veins crosscutting the limestone beds and penetrating the intrusive rock. The belt includes small masses of chalcopyrite, magnetite, and pyrrhotite, which constitute the copper ores.

Besides occurring disseminated in the contact deposits and in veins, garnet is a primary mineral in some of the pegmatitic phases of the diorite, where it has invariably been observed to be isotropic in thin sections. In its other occurrences it is more or less doubly refracting.

Epidote.—Epidote, a calcium-iron-aluminum silicate, occurs principally as a gangue mineral in the contact deposits, in places forming large crystal aggregates with garnet quartz and calcite. (See Pl. VIII, *D*.) These crystals are large and brilliant, being usually dark green with light-green reflections. Many of them are twinned, showing striated faces, and in certain instances are truncated at both ends with numerous faces. The most perfect of these crystals were found on the Green Monster Mountain on the east side of the Copper Mountain intrusive mass. Specimens of these epidote crystals were described as follows by Dr. Charles Palache,[1] of the Harvard Mineralogical Laboratory:

> The specimens at hand consist of several loose and a magnificent cluster of large crystals implanted on massive epidote. The only associated mineral is quartz in small clear crystals of later formation than the epidote.
>
> The epidote is very dark green to greenish black in color, but oil-green and translucent in thin crystals or where bruised or cracked. The larger crystals are in the form of nearly square tables, which measure as much as 5.5 centimeters each way and 3 centimeters in thickness. In the smaller crystals the tabular habit is less pronounced, and the mineral sometimes assumes the ordinary prismatic habit parallel to the *b* axis. The crystals are not infrequently doubly terminated. In the large group to which reference was made about 20 of the tabular crystals are found on a surface measuring about 15 by 20 centimeters, several of the crystals being over 3 centimeters on an edge, and attached by an edge in such fashion as to present an appearance altogether foreign to epidote. The crystals are frequently twinned according to the ordinary law for epidote, the twinning plane being the orthopinacoid.

To this Dr. Palache adds a list of crystallographic forms determined on the crystals and illustrates these by drawings. In conclusion he states that the Alaska epidote ranks among the finest occurrences of American crystallized minerals and is surpassed in the size, beauty, and complexity of its crystals only by the epidote from Knappenwand, in the Tyrol.

Quartz.—The mineral quartz (silicon dioxide), which is easily distinguished by its glassy appearance, is not so abundant in this district as in most mineralized regions. In the contact deposits it occurs only in small amounts and is generally well crystallized and associated with crystals of garnet and epidote. (See Pl. VIII, *D*.) Many of the crystals are doubly terminated and some are very large, the largest noted being 10 centimeters long. The quartz is usually superposed on the garnet and epidote crystals and also surrounds the ore minerals, thus indicating that it was the last mineral to form.

In the vein deposits it is associated with calcite, both minerals occurring with the ore or in veinlets that intersect the ore veins.

In the Jumbo mine a cleavable variety of quartz, containing numerous minute needles of hornblende, is associated with chalcedony.

Calcite.—Calcium carbonate (calcite), commonly known as carbonate of lime, is of widespread occurrence. It is readily recognized by its perfect cleavage and its softness. Calcite is particularly prominent in the contact deposits and also occurs in the vein deposits. Where it is associated with garnet and epidote it is usually of later formation and in many places fills the interstices between crystals of these minerals. (See Pl. IX, *A*, *B*.)

Diopside.—Diopside, a calcium-magnesium pyroxene, is a prominent gangue mineral of the contact deposits and is one of the principal constituents of the contact rock. In appearance it resembles epidote, for which it is often mistaken. Its color ranges from pale to deep green and it is generally scattered through the rock in minute crystals and grains, or it forms aggregates of needle-shaped crystals in veinlets and immediately at the borders of the contact rock. (See Pl. VII, *C*.)

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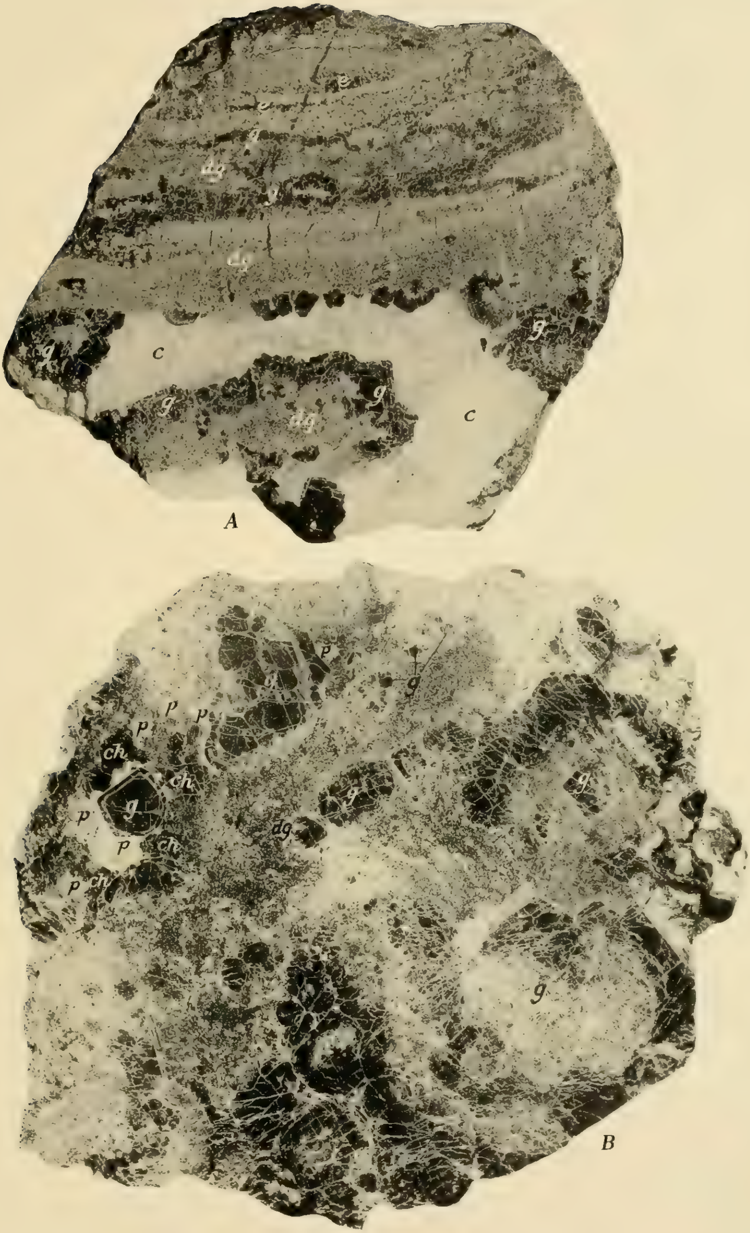
[1] Am. Acad. Arts and Sci. Proc., vol. 37, No. 19, pp. 531–535, March, 1902.

PLATE IX.

A. Massive contact rock from contact zone on Jumbo claim No. 4. In the groundmass of garnet-diopside and calcite are large, irregular crystals of garnet, which show marked zonal structure. This specimen contains some pyrite and pyrrhotite. *c*, Calcite; *e*, epidote; *g*, garnet; *dg*, calcite, diopside, garnet.

B. Contact rock showing vein structure. This rock is made up essentially of garnet, diopside, and some calcite and is traversed by veinlets bordered with garnet crystals and filled with calcite, which was introduced subsequent to the formation of the garnet. *g*, Garnet showing zonal structure; *p*, pyrite; *ch*, chalcopyrite; *dg*, calcite, diopside, garnet.



CONTACT ROCKS FROM COPPER MOUNTAIN AREA.

Scapolite.—Scapolite, a calcium-aluminum silicate containing sodium and chlorine, occurs in veins in the vicinity of the ore deposits in prismatic crystals 1 inch or 2 inches in length, with rough, uneven faces, and varies from white to gray in color. It also replaces feldspar in the diorite near certain contacts. It was found only in the vicinity of the Copper Mountain deposits and is not common. (See Pls. VII, *A*, and VIII, *B*.)

Amphibole.—The hornblende variety of amphibole, a calcium-magnesium-iron silicate, is a common but not abundant gangue mineral in some of the copper contact deposits. At the Jumbo No. 1 mine it forms clusters of crystals in the magnetite ore. It is also present in the older schists which have been altered by the contact rock. (See Tremolite, below.)

Wollastonite.—The metasilicate of calcium, wollastonite, forms radiating clusters of crystals in the garnet and diopside contact rock. It also occurs in finely radiating crystals in the limestone and quartzites and in the diorite a short distance from the intrusive contact. It belongs with the minerals of the contact deposits, but its occurrence away from the contacts suggests that the heat required for its formation was not so great as that required to produce the garnet and diopside, which occur at the contacts.

Orthoclase.—Orthoclase is intimately associated with diopside, garnet, and calcite (see Pl. X, *C*); it appears both in compact masses that show no cleavage and in cleavable grains. Its occurrence in grains, however, is rare. The variety adularia occurs in druses at the Jumbo mine in well-formed crystals nearly a centimeter long. Quartz and biotite crystals incrust much of the adularia. (See Pl. VIII, *F*.)

Biotite.—Biotite occurs as a later mineral in the veins with adularia at the Jumbo mine.

Dolomite.—Cavities in the contact rock have furnished a few small specimens of dolomite in rhombohedral crystals.

Spinel.—Small octahedral crystals of the dark-green spinel, pleonast, were observed accompanying the clear diopside in the Green Monster mine.

Serpentine.—Serpentine appears in two very different forms—(1) as irregular yellowish, slickensided masses in the dolomitic limestone, and (2) as small, globular, radial-fibrous aggregates evenly distributed through the limestone. The aggregates are almost microscopic in size and are nearly white. One specimen of limestone containing about 30 per cent of these spherules could not be distinguished in color from a pure limestone.

Tremolite.—Tremolite occurs as loose felty masses of slender white fibers in the limestone at the Green Monster claim. It was also noted at other localities, but only in small quantities.

Talc.—Talc was one of the last minerals to form in some of the veins and is found in druses of quartz; also along slipping planes in the ore bodies.

Zoisite.—Zoisite is usually associated with epidote, the two minerals in some places growing side by side apparently contemporaneously. Clusters of pink zoisite were also noted in veins of diopside.

Clinochlore.—Druses probably containing clinochlore, a soft greenish-blue micaceous mineral, were observed in the ore masses of the Jumbo No. 4 claim. This mineral is a hydrous silicate of magnesium and aluminum and is of secondary origin.

Zeolites.—Three varieties of zeolites were collected in the Copper Mountain area, namely, stilbite, chabazite, and heulandite, all hydrosilicates of aluminum with calcium and sodium. They were found in cavities formed in the tongue of contact rock just south of Summit Lake. They are secondary minerals occurring as druses with garnet and epidote crystals. The stilbite (see Pl. X, *A*) occurs in characteristic sheaf-like aggregates and the chabazite in nearly cubic rhombohedrons about a quarter of an inch in diameter. Heulandite was also noted in the form of flakes upon the stilbite crystals.

MINING IN THE COPPER MOUNTAIN AREA.

GENERAL CONDITIONS.

Copper is now (1908) being produced by only one large mine in the Copper Mountain area—the Jumbo mine, belonging to the Alaska Industrial Co. In past years the mines of the

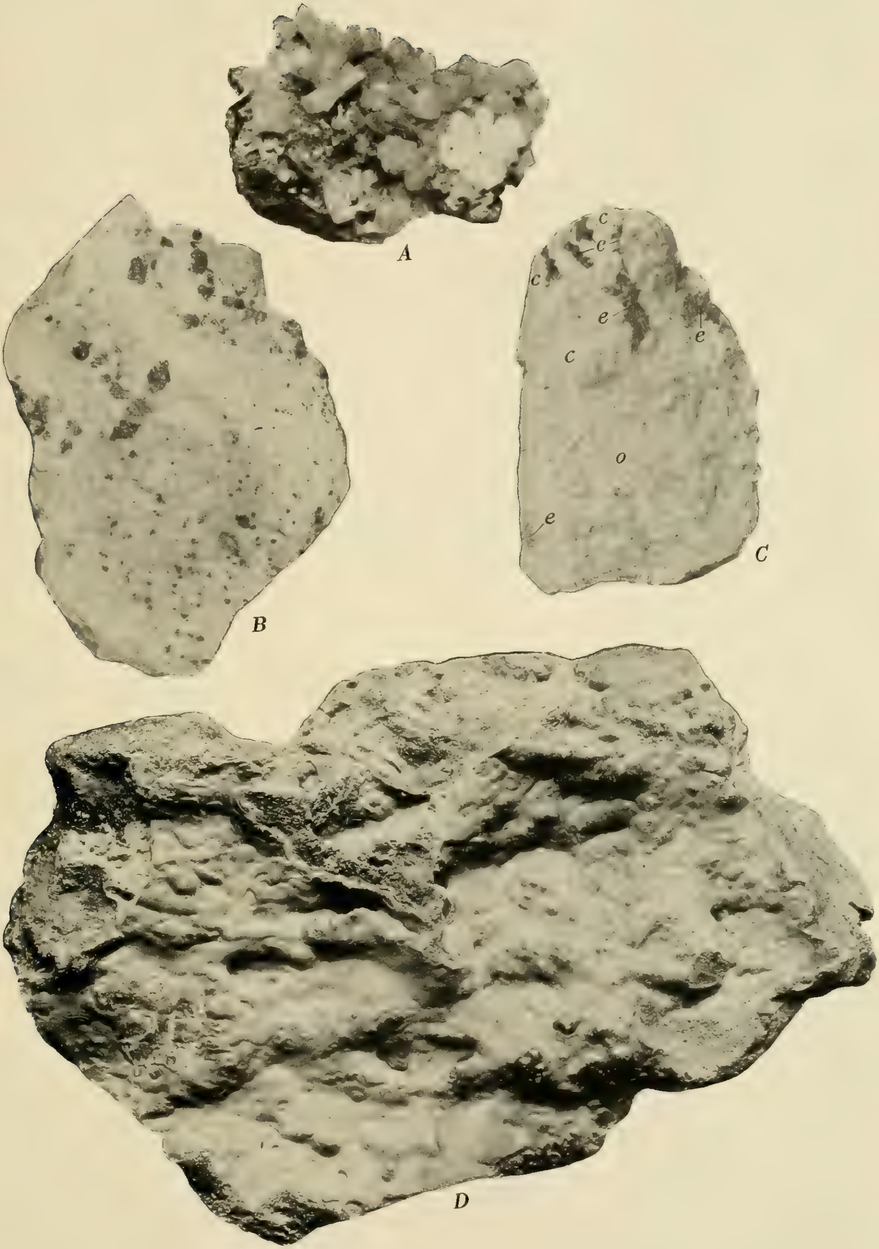
PLATE X.

A. Groups of crystals of stilbite, which occurs with chabasite in druses in the garnet-diopside-calcite contact rock. Specimen from tongue of contact rock south of Summit Lake.

B. Specimen from pegmatite dike in granite on Jumbo claim No. 4, showing quartz and feldspar and small disseminated crystals of garnet.

C. Orthoclase with epidote and some calcite from veinlet in contact rock on New York claim, Copper Mountain group. *c*, Calcite; *e*, epidote; *o*, orthoclase.

D. Malachite from surface workings on New York claim of Copper Mountain group. Underneath the coating of malachite there is some azurite and cuprite, with limonite.



MINERALS AND ORE FROM COPPER MOUNTAIN AREA.

A. SMELTER AND SAWMILL AT HEAD OF COPPER HARBOR.

An aerial tramway leads from the mine workings to the smelter. Photograph by Winter & Pond.

B. HETTA MOUNTAIN FROM HEAD OF COPPER HARBOR.

Photograph by Winter & Pond.

Alaska Copper Co. also have been productive, and small shipments of copper ore have been made from the Corbin and Copper City mines. Most of the ore shipped from these mines contains over 100 pounds of copper and a few dollars' worth of gold and silver per ton. The quantity of ore mined, however, is relatively small, and the underground workings, except those of the Jumbo mine, are not extensive. Mining presents no serious difficulties, as most of the deposits are located well up on the mountain sides, so that they can be developed by short tunnels, and the distance from the sea to most of the mines is only a few miles.

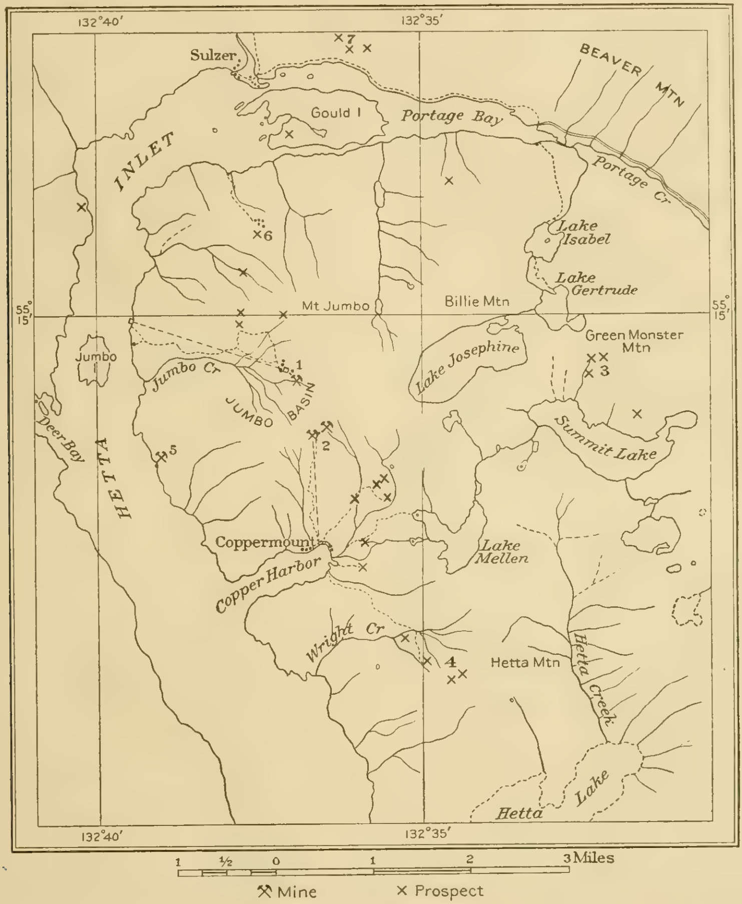


FIGURE 1.—Sketch map of the Copper Mountain area showing location of principal mines and prospects in 1908. 1, Jumbo mine, Alaska Industrial Co.; 2, Copper Mountain mines, Alaska Copper Co.; 3, Green Monster claims, Alaska Industrial Co.; 4, Hetta Mountain claims; 5, Corbin mine, Alaska Metals Mining Co.; 6, Houghton claims, Cuprite Copper Co.; 7, Sultana claims.

EARLY DISCOVERIES.

Mining development on Copper Mountain began in 1897, though the existence of copper ores in this region was known some years before by the natives who fished and hunted along the coast. The first mining claims were located on the ridge just west of Copper Mountain peak, where copper carbonate and other oxidized ores outcrop. These claims were staked and recorded by Charles Reynolds and Thomas Wright in the autumn of 1897. In the same year the deposits in the Jumbo Basin were discovered by Aaron Shellhouse, but they were not recorded until the following spring. In 1898 many other claims were located on Copper Mountain, and also on Green Monster Mountain, to the east, and on Hetta Mountain, to the south. The first man to interest capital in developing the Copper Mountain properties was Henry W. Mellan, through whose efforts the Alaska Copper Co. was formed, and development work was started in 1899.

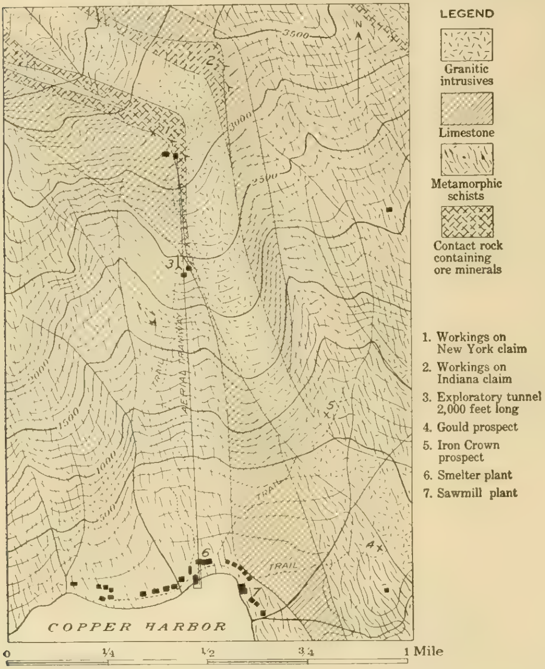


FIGURE 2.—Sketch map showing geology and mine workings on property of Alaska Copper Co. and adjacent mining claims in 1908.

The Jumbo Basin deposits, on the west slope of Copper Mountain, were visited in 1899 by William Sulzer, who recognized their value and formed the Alaska Industrial Co. to develop these deposits.

Many other claims were located in the vicinity of Copper Mountain between 1900 and 1903, including the Corbin, Houghton, Hetta Mountain, and the Sultana group.

THE MINES.

ALASKA COPPER CO.

Location of property.—The group of claims belonging to the Alaska Copper Co. occupies the south slope of Copper Mountain, extending from tidewater at Copper Harbor to the crest of the ridge at an elevation of 3,500 feet. (See fig. 2.) There are 18 claims in the original group, though developments have been advanced mainly on the New York and Indiana claims, which are on the top of the ridge.

Development.—The first developments were made by means of open pits on the outcrops of the ore deposits along the ridge, at altitudes of 3,300 and 3,400 feet. The lower of these outcrops is now (1908) on the New York claim, and tunnels 200 and 700 feet in length have been driven at levels 150 and 300 feet below the open pit to explore the deposit. These tunnels are connected by raises. Some stoping done in the tunnels showed that the ore was irregular in its occurrence and that it consisted of rich pockets of copper carbonate. In the low tunnel the carbonate ore is replaced by sulphides, which are more disseminated in the garnet gangue rock, though the rock contains also carbonate ores. This deposit has been explored at still greater depth by a tunnel 3,000 feet long, this measurement including crosscuts. This tunnel is run at an elevation of 2,350 feet and undercuts the surface outcrops of the ore deposit at a depth of nearly 1,000 feet. It follows the contact zone of the diorite, first with quartzite and next with limestone, and the tunnel itself zigzags from one contact to the other, usually keeping within the contact rock. Its general course is northeasterly to a point 1,400 feet from its mouth, where it branches, the left or northwestern branch continuing for several hundred feet along the contact to a point almost directly under the surface outcrop on the New York claim and the northeastern branch penetrating the massive granite belt for 700 feet toward the Indiana lode. (See fig. 3.)

The principal developments on the Indiana claim are at a point 800 feet northeast of the open pit on the New York claim and at an elevation of 3,500 feet. Here a large open pit has been made and tunnels have been driven at different points, from 40 to 220 feet below the level of the pit, to investigate the deposit in depth. These openings are all in the contact rock and include about 600 feet of exploratory tunnels, crosscuts, and raises, but only small masses of minable ore have been found in them. An eastward extension of the tunnel at the 2,500-foot level would probably traverse the same contact rock at a depth of 1,150 feet below the surface. From the Indiana workings a surface tram, 1,400 feet long, extends around the mountain to the New York claim, from which an aerial tram extends to Copper Harbor. Pits, trenches, and short tunnels, most of them in the contact rock, have disclosed some ore on other claims belonging to this group, but no large masses have been found on these claims and the work done on them has been small. The total mine development up to the time the mine closed in 1907 consisted of about 4,200 feet of tunnels and 500 feet of shafts and raises, besides many open pits. The ore mined has been taken principally from the upper workings on the New York claim.

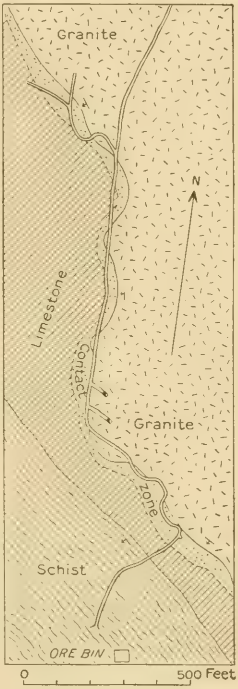


FIGURE 3.—Plan of long tunnel of Copper Mountain mine, showing rocks near contact zone.

Smelter.—The smelting plant stands close to tidewater at the head of Copper Harbor. It consists of a 250-ton Allis-Chalmers blast furnace, ore bins of 2,500 tons capacity, coke bins of 1,200 tons capacity, and a sampling mill, besides the usual appliances for granulating and removing slag. (See Pl. XI, *A*.) The ore from the mine workings is delivered to the sampling mill bin by an aerial tramway 6,000 feet long, and the ore shipped to the smelter is unloaded on the wharf into receiving bunkers of 1,000 tons capacity, from which it is drawn off into cars and hoisted on an inclined tramway to the sampling mill.

In addition to the smelting plant there is a sawmill, machine shop, store and warehouse, assay office, and compressor plant. The power required for the smelter and compressor plant was derived from Reynolds Creek, the water being transmitted 1,000 feet by a 22-inch pipe line to two 300-horsepower Pelton wheels.

The smelter was first blown in for a run in June, 1905, and was operated for short periods during 1906 and 1907. The mines above the smelter did not furnish enough ore for the furnace and for fluxing and it became necessary to go to other mines for ore. The Rush & Brown mine, on the east coast of the island, was therefore leased by the Alaska Copper Co., and small lots of ore were purchased from other mines on Prince of Wales Island. The smelter was run at intervals on these ores until early in 1907, when it was shut down, and no attempt has yet been made (1912) to operate it again.

Ore deposits.—The two principal ore deposits that have been developed on the New York and Indiana claims are contact deposits separated from one another by a belt of diorite 800 feet wide. Along both sides of this belt of intrusive rock lie zones of contact rock, composed essentially of garnet-diopside and epidote, and in these zones the ore is found either scattered or in concentrated masses. At the surface workings on the New York claim a mass of rich ore occurs in the contact rock between the diorite and limestone, the limestone forming the hanging wall. (See Pl. VI, *B*, p. 32.) Most of the copper ore, which was originally chalcopyrite, has been altered to copper carbonates and limonite, and these secondary ores have spread out into the somewhat fractured limestone hanging wall. This spreading, which is attributed to the action of meteoric waters, in few places extends more than 50 feet into the hanging wall. On the surface this ore mass appeared to be extensive, but in the tunnels below the surface pit it was rather small, and in the long tunnel that follows the contact for 2,000 feet only scattered chalcopyrite was found and no minable ore. (See fig. 3.) In the upper tunnels the secondary ores were less prominent than in the surface pit and in the long tunnel they were entirely absent. The contact rock exposed along the surface and in the long tunnel ranged in width from a few feet to 50 feet. In two places veins of this contact rock that occupied fissures in the diorite had been followed for short distances by crosscuts from the main tunnels. The contact rock contained inclusions of both the limestone and the quartzite. Faulting and slipping planes were observed within the contact rock, but the displacements along these were slight.

The contact deposit on the Indiana claim is on the eastern contact of the diorite belt. Quartzite and amphibolite cut by numerous quartz stringers form the hanging wall, though the contact rock includes masses of limestone. The garnet and epidote minerals of the contact rock have penetrated and altered these quartzites for a few hundred feet away from the contact. The ore exposed in the open pit and tunnels is similar to that on the New York claim, though it is less concentrated, and the valuable metals it contains are more scattered. The ore mined from this deposit contained only a little copper and from $1 to $2 in gold and silver. At both the New York and Indiana contact deposits there is a gradual change or blending of the contact rock and ore into the diorite, due to replacement of the minerals composing the diorite by those composing the contact rock. This zone of partial replacement is generally from 2 to 5 feet wide. The contact action is fully discussed under a separate heading (p. 102).

ALASKA INDUSTRIAL CO.

Location of properties.—The present (1908) holdings of the Alaska Industrial Co. in the Copper Mountain area include the Jumbo group (29 claims) and the Green Monster group (14 claims) located on Green Monster Mountain. (See Pl. IV, *A*, p. 29.) The mining developments here described include only those made up to 1908. Since then some other notable advances have been made.

JUMBO GROUP.

The claims of the Jumbo Group occupy the slopes of Jumbo basin, on the northwest side of Copper Mountain. These claims extend from a point 500 feet in elevation and a mile from tidewater nearly to the mountain summit, which stands at an elevation of 3,946 feet. The main deposits being explored lie at elevations between 1,500 and 1,900 feet, on the east slope of Jumbo Basin, on Jumbo claims Nos. 1, 1A, and 2, and between elevations of 1,500 and 2,000 feet on Jumbo claims Nos. 4 and 14. Practically all the ore mined and shipped has been taken from the deposits on Jumbo claim No. 4.

Development.—The deposits included in the Jumbo group were first exploited in 1902, and during succeeding years numerous prospect tunnels were driven and test pits sunk on the different claims. After a promising ore body had been opened on claims Nos. 4 and 14, located at elevations of 1,700 and 2,050 feet above sea level, it was necessary to devise a means of transporting the ore to tidewater. For this purpose a Riblett aerial tram 8,250 feet long and an additional tram 600 feet long were erected in 1905–6, thus connecting the beach with the lower tunnel of the mine workings, 1,700 feet above sea level. At the beach a wharf with a frontage of 150 feet was built and ore bins of 4,000 tons capacity were erected. While this work was in progress the development of the ore deposits was advanced, and early in 1907 shipments of the ore to the Tyee smelter, in British Columbia, were begun. In 1908 the mine workings on Jumbo claim No. 4 consisted of four tunnels at elevations between 1,570 and 1,950 feet, and an open cut at an elevation of 2,050 feet. (See fig. 4.) The main working tunnel, or tunnel No. 3, is at an elevation of 1,700 feet. At a point 180 feet from its mouth a 130-foot vertical raise connects this tunnel with the stopes in the ore body and with tunnel No. 2. At a point 40 feet above tunnel No. 3 a stope has been extended to the west and 30 feet above this an exploratory drift has been run eastward into the ore. The floor of the main stope is 100 feet above the level of tunnel No. 3. This stope is 240 feet long, 10 to 40 feet wide, and extends for 30 feet above the level of tunnel No. 2. A second sulphide body, separated

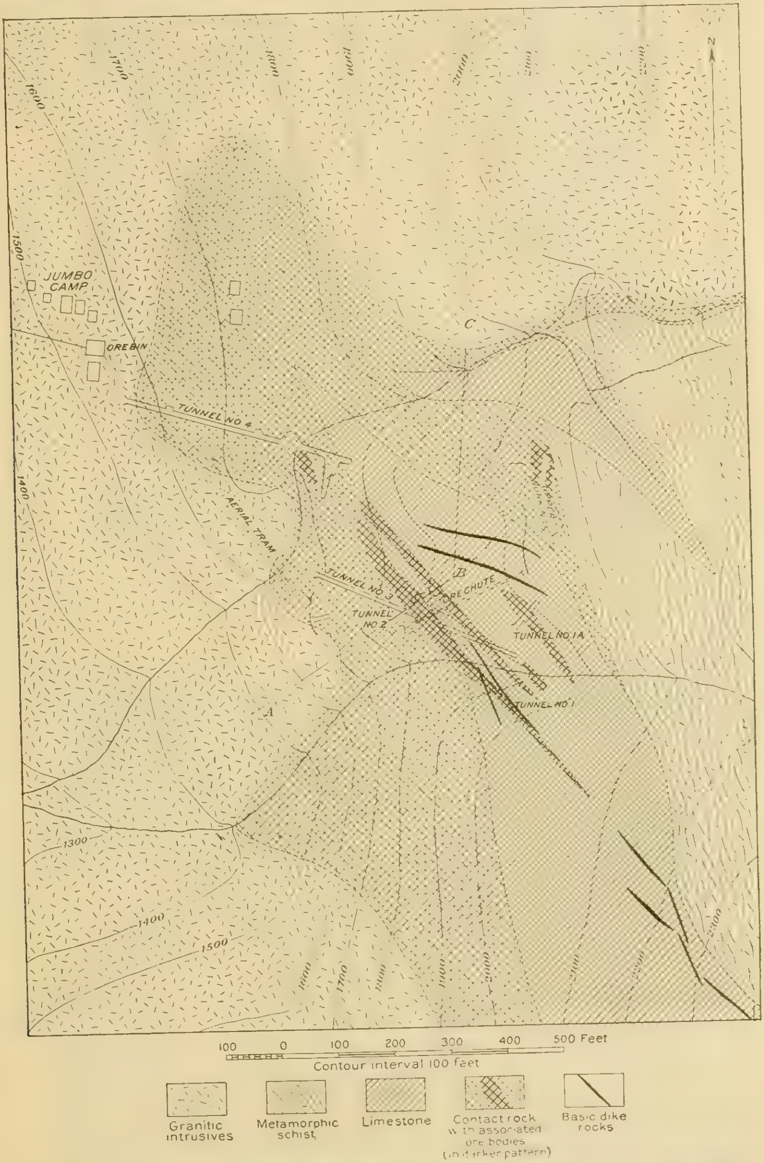


FIGURE 4. –Geologic sketch map showing surface geology and mine developments (1908) on Jumbo claim No 4. *A B C*, line of cross section, figure 5.

from the main deposit by 40 feet of contact rock, has been opened on level No. 2, northeast of the main deposit, and has yielded a large quantity of ore. The ore from these two ore bodies goes through the raise to tunnel No. 3, where it is trammed to the upper terminal of the aerial tramway, from which it is carried to the ore bunkers at the shore.

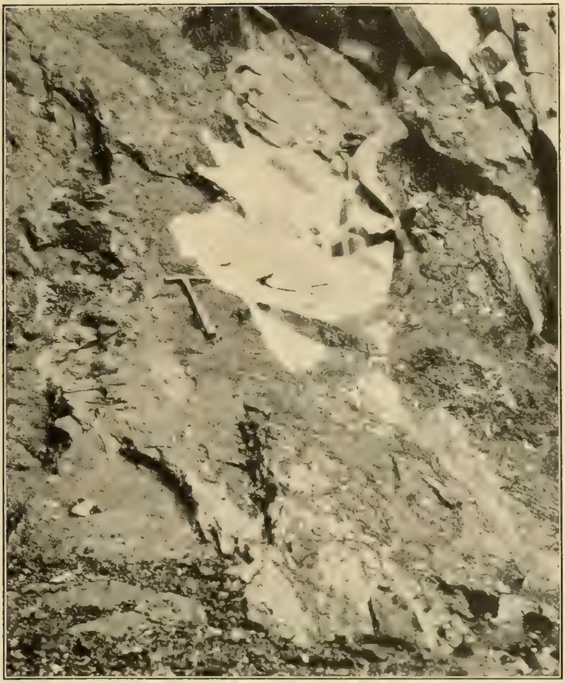
The southeastern extension of these deposits is being explored by tunnels in Canyon Creek. In tunnel No. 4, which is at an elevation of 1,570 feet, just above the upper terminal of the tramway, two small ore bodies were crosscut and yielded a small quantity of ore. These bodies may represent the northwestern extension of the two ore deposits opened in tunnel No. 2. This level is being advanced to undercut the raise in tunnel No. 3 and will eventually serve as a passageway for all the ore mined from the workings above, thus eliminating the necessity of the auxiliary tramway from tunnel No. 3.

The uppermost workings consist of an open cut across a width of 200 feet at an elevation of 2,050 feet, on Jumbo claim No. 14. In this cut the irregularity and sporadic occurrence of the ore is well shown. At one point a face of massive sulphide ore 6 feet across is surrounded by barren gangue rock; at other points sulphides were finely disseminated in the rock in sufficient amounts to make a minable ore.

The developments on Jumbo claim No. 1 have been extensive and have exposed a large body of low-grade ore. The uppermost workings are at an elevation of 1,890 feet and consist of an open cut exposing considerable copper carbonate and limonite ore in the contact rock. This carbonate, however, does not extend to a great depth. Just below this cut the deposit is exposed in a steep bluff 100 feet high and 100 feet wide, along the foot of which the ore consists of masses of sulphides accompanied by magnetite. Below and west of this point, at an elevation of 1,660 feet, a tunnel crosscuts the limestone hanging wall and enters the contact rock, which at that point was barren. Another larger bluff of ore is exposed east of this tunnel, at an elevation of 1,580 feet, on Jumbo No. 2 claim. This deposit, known as the magnetite body, has been undercut by two tunnels, one at 1,540 and the other at 1,480 feet. The upper tunnel starts in the magnetite deposit, penetrates it for 50 feet, and enters the diorite footwall for 6 feet. The contact between the ore body and the footwall showed a gradation from the contact rock and the intrusive rock, though the gradation was rather abrupt. Near the contact the ore is of fine texture, is rich in diopside and magnetite, and contains disseminated sulphides, whereas at the entrance to the tunnel the gangue is essentially garnet and calcite, with small masses of chalcopyrite. The lower tunnel crosscuts the limestone hanging wall for 55 feet and penetrates the ore body for 10 feet. The contact between the ore body and limestone is sharply defined. The downward extension of this ore body is exposed on Jumbo claim No. 1A by two tunnels, one above the other, at elevations of 750 and 840 feet. The upper tunnel crosscuts a hanging wall of schist that is largely replaced by the contact rock and enters the sulphide ore 25 feet from its mouth. In the lower tunnel, which is 240 feet long, the hanging wall consists of a banded quartzite or silicified schist, which grades into banded contact rock containing disseminated sulphides and magnetite. The inner end of the tunnel extends into the diorite footwall. The contact deposit exposed in this tunnel is 100 feet wide, but the ore in it is scattered and is of lower grade than the ore exposed in the upper tunnels. Explorations on Jumbo claim No. 3, which lies between the workings on Jumbo claims Nos. 2 and 4, have exposed other deposits of chalcopyrite and magnetite, on which developments are being advanced. Disseminated deposits of sulphides in the schists have been explored by tunnels and open cuts on Jumbo claims, but the metallic content of the ore exposed was low.

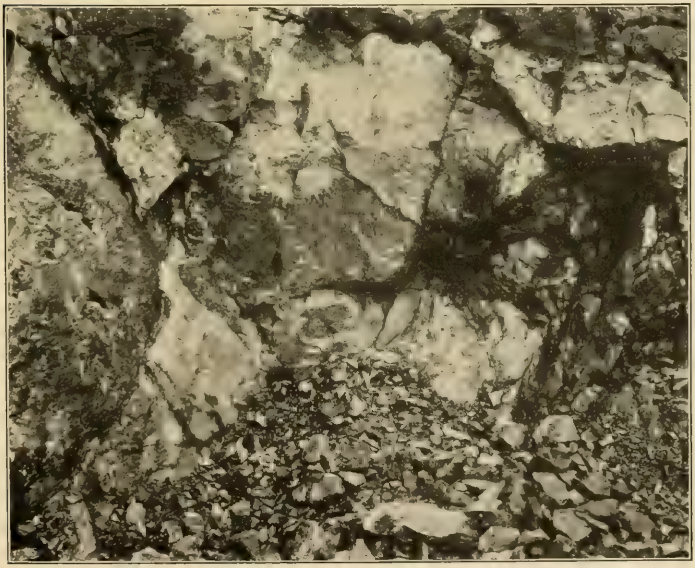
Ore deposits.—The general relations of the rocks of this area, which are similar to those in the Copper Mountain group, already described, are presented on the geologic map (Pl. I, p. 16) and in the sketches of the mine workings (figs. 4 and 5). The main diorite mass forms the footwall of the deposits, the hanging wall being in some places a crystalline limestone and in others a silicified schist or banded quartzite much metamorphosed and varying in color from gray to greenish and reddish.

The copper deposits being mined on Jumbo claim No. 4 consist of irregular bodies of chalcopyrite-pyrrhotite ore, 10 to 40 feet wide and 100 to 200 feet long, One mass has been opened for a depth of 150 feet, but the extent of the others is not known. The contact zone



A. MASS OF LIMESTONE INCLOSED IN CONTACT ROCK.

Point of hammer rests on reaction rim composed essentially of amphibole. (See Pl. VIII, *C*.) View taken just below tunnel No. 1, Jumbo claim No. 4.



B. MASS OF CHALCOPYRITE ORE INCLOSED IN CONTACT ROCK.

Dark patch on right is massive chalcopyrite. View taken just above mouth of tunnel No. 2, Jumbo claim No. 4.

within which these masses occur (see figs. 4 and 5) lies between the granitic intrusive and a belt of limestone, above which metamorphic schists appear. This mineralized zone is nearly surrounded by the granitic contact and in this respect differs from the other contact deposits.

No definite line of separation between the contact rock and the granitic intrusive can be drawn, as the mineral solutions appear to have replaced the mineral components of the rock adjacent to the contact. The beds of limestone on the hanging-wall side of the contact zone are fractured and faulted and masses of limestone are completely inclosed in the contact rock. (See Pl. XII, *A*.) On the other hand, masses of the contact rock are surrounded by the limestone, suggesting the replacement of the limestone by ore-bearing minerals. The contact rock is composed mainly of garnet, diopside, epidote, and some calcite, and these minerals are in places so closely associated as to resemble a compact felsitic rock, so that the rock might be mistaken for felsite. Near the ore masses the contact rock is generally coarsely crystallized, the garnet, epidote, and diopside forming aggregates of well-developed crystals and the calcite filling the interstices between the crystals. In the ore bodies the chalcopyrite occurs in small masses or is scattered through the inclosing contact rock and is associated with pyrrhotite and pyrite. Except the local change in the character of the crystallization of the contact rock there are no indications within the contact zone that may be used as a guide in the search for these ore masses.

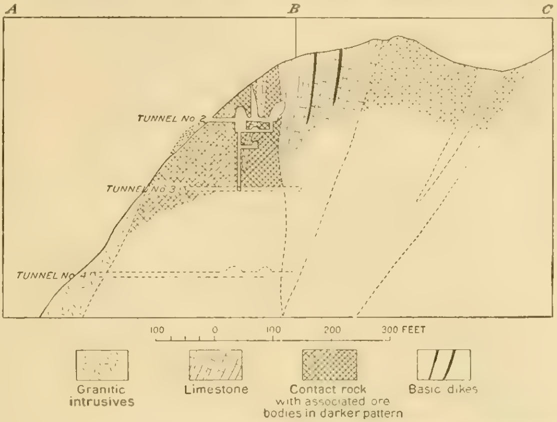


FIGURE 5.—Cross section along line *ABC* on figure 4, showing geology and mine developments (1908) on Jumbo claim No. 4.

The ore bodies on Jumbo claims Nos. 1 and 2, though similar in most respects to those on Jumbo claim No. 4, contain less copper and more magnetite, a mineral that was notably absent from the deposit on the Jumbo No. 4. The ore bodies have been well exposed by erosion over broad areas and in places are in the form of a sheet a few feet wide overlying the diorite footwalls. (See fig. 6.) These outcrops occur between the 1,500 and 2,000 foot contours, above which the diorite alone was observed. The width of the contact rock between the hanging wall and footwall varies from 10 to 100 feet, though in places the diorite and limestone lie in direct contact. The ore bodies within this contact zone are from 5 to 50 feet in width and a few hundred feet in length. They have not been developed to any considerable depth. The ore masses are confined to the diorite footwall and are sporadic in their occurrence, though they are connected with one another by more or less barren gangue or contact rock. The average ore from this deposit contains a high percentage of iron and nearly sufficient silica for smelting. (See fig. 6.) The ore carries not only copper but gold and silver.

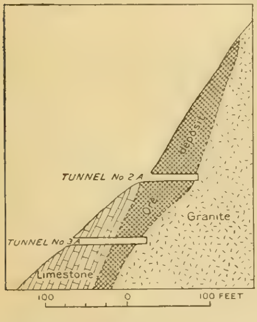


FIGURE 6.—Cross section of magnetite deposits on Jumbo claim No. 2 (1908).

GREEN MONSTER GROUP.

Situation.—The Green Monster group of claims occupies the northern and western slopes of Green Monster Mountain, 2½ miles east of Copper Mountain and 3 miles from the tide flats at the head of Portage Bay, from which a route, partly by trail and partly by boat, crossing two lakes each half a mile wide, at altitudes of 600 and 1,680 feet, respectively, leads to the principal mine workings, at an elevation of 2,800 feet. Another approach to these claims, also partly by trail and partly by boat, is from Copper Harbor, as indicated on the map (Pl. II, p. 28) and on figure 1.

Development.—Although these claims were located in 1900, developments up to 1908 have been meager, and no attempt has been made to advance the exploration beyond the required assessment work. Two tunnels have been driven, each 65 feet long, one on Green Monster claim No. 1 and the other on Diamond B. claim. On the Iola claim a pit 8 feet deep has been sunk and trenches have been dug along the ore body.

Ore bodies.—Ore bodies at the contact of the limestone and diorite are found on the Iola, Black Warrior, and Diamond B. claims. The deposit on the Iola claim has been opened by a small pit and by surface stripping and consists of a mass of magnetite-chalcopyrite ore, 10 feet wide, inclosed in the garnet-epidote gangue, which at this point occupies a width of about 25 feet between the limestone hanging wall and the diorite footwall. Along this contact other smaller ore masses were observed on the Iola and Black Warrior No. 2 claims, but they were apparently of little consequence. On the Black Warrior claims Nos. 1 and 5 similar ore deposits lie adjacent to the contact of the diorite and limestone and in a black slate band that extends along the mountain crest, striking N. 30° W., but these deposits have not been prospected. On the Diamond B. claim a tunnel 65 feet long has been driven along the contact of the limestone with a porphyritic dike 50 feet or more in width, striking N. 30° E. The main contact of the diorite lies about 150 feet to the west. The face of the tunnel is in limestone and in the tunnel the garnet-epidote vein rock is exposed across a width of about 10 feet and for a length of 50 feet. Small masses of copper sulphide occur in this contact rock, but the metal content of the vein as a whole is low.

A vein deposit filling an irregular fissure in the limestone occurs on Green Monster claim No. 1. This vein appears to be an offshoot from the main contact zone just west of it. The vein is undercut by a tunnel 65 feet long and is exposed by trenches for 250 feet along the surface. The vein strikes S. 20° E., dips vertical, and averages 6 feet in width. The copper occurs in small masses and disseminated particles throughout the garnet-epidote-calcite gangue. Associated with the chalcopyrite ore is pyrite, and in places along the surface limonite, malachite, and azurite occur.

A third type of mineralization is exposed on Black Warrior claim No. 2, where a narrow vein containing galena, pyrite, and chalcopyrite has been deposited along the contact of a porphyry dike and the limestone country rock at a point about 1,000 feet from the granite contact. This ore, though of good quality, has not been found in large quantity.

In general the ore bodies on the Green Monster group are similar to those on the Jumbo group, but do not appear to be as great in size and extent. The position of the property necessitates the building of a tramway for 3 miles in order to ship the ore, and conditions of mining are less favorable here than at many other points along the coast.

CUPRITE COPPER CO.

Situation and development.—The property of the Cuprite Copper Co., known as the Houghton group of claims, is on the northwest slope of Mount Jumbo, between elevations 1,000 and 2,000 feet, and is 1 mile from Hetta Inlet. (See fig. 1.) They include the diorite contact zone exposed on the Jumbo group to the south, and the ore bodies under exploration are of the same general type. The claims, including a mill site at tidewater, were located in 1901, and from that time to the end of 1905 the developments were meager, assessment work alone being done. Early in 1906 the properties were acquired by the Cuprite Copper Co., two more claims were located, and active development was begun and was continued during 1907 and 1908. The present mining camp is at an elevation of 1,500 feet and the mine workings between 1,600 and 1,700 feet. A tunnel at an elevation of 1,600 feet, 100 feet long, and another at 1,700 feet, 80 feet long, had been driven in 1908 to explore the ore body along the contact, its surface exposure being 100 feet above. At other points on these claims short exploratory tunnels and cuts have been made.

Ore body.—The copper deposits on which explorations are being made is included in the garnet-epidote contact rock, which occupies a zone 25 to 75 feet wide between the diorite and limestone. This zone strikes N. 45° E. and dips steeply to the northwest. The ore body is developed on the surface by a 30-foot cut and a 15-foot pit, in which a body of massive chalcopyrite ore 5 feet wide is exposed. In the tunnels that enter the contact zone small amounts of copper ore have been found but no large ore body. The chalcopyrite is associated with magnetite, pyrite, and some pyrrhotite. These claims showed less general contact metamorphism and less ore than the Jumbo group.

SULTANA GROUP.

Situation and development.—The Sultana group, consisting of six claims, is on the north side of Hetta Inlet, about a mile east of Sultana, and extends from tidewater to an elevation of 1,000 feet on the south slope of Beaver Mountain. The principal developments have been made on the Sultana claim, though prospecting has been advanced on the adjoining claims, the Index and Vulcan. The total work done each year up to 1908, however, amounts to little more than the assessment work.

Ore bodies.—The ore bodies exposed are contact-metamorphic deposits underlain by a granitic intrusive, banded siliceous limestone forming the hanging wall. A gangue of garnet and epidote, with considerable calcite, has been deposited along the contact, in which sulphides of copper and iron are sparingly distributed in small masses and disseminated particles.

At a point on the Sultana claim at an elevation of about one-third of a mile from the shore a tunnel 130 feet long was driven in the granodiorite footwall without discovering ore. Another tunnel 430 feet in elevation exposes at its entrance a mass of chalcopyrite ore 3 feet wide and then crosscuts the garnet-epidote gangue rock for 25 feet, showing practically no ore. On the Index claim, which is east of the Sultana claim, at an elevation of 600 feet, an open cut 60 feet long exposes small amounts of chalcopyrite, not sufficient to make a profitable ore, associated with magnetite and pyrrhotite in banded garnet-epidote rock. On the Vulcan claim, north of the Sultana claim, at an altitude of 520 feet, is an open cut 60 feet wide. Here garnet-epidote rock occurs with large included fragments of banded limestone containing pyrrhotite and chalcopyrite in masses a few feet wide. A relatively small amount of ore is developed on these properties. The ore at this prospect was reported to carry cobalt in considerable amount, but a sample taken by the writer and submitted for analysis gave only a trace of cobalt and less than 0.2 per cent of nickel.

ALASKA METALS MINING CO.

Situation and development.—The property of the Alaska Metals Mining Co., formerly the Corbin mine, is close to tidewater on the east side of Hetta Inlet, 1½ miles north of the entrance to Copper Harbor. This property, which includes four claims, was located in February, 1905, and the following summer ore was shipped to the smelter at Coppermount. Early in 1906 the mine was sold to the Alaska Metals Mining Co., which began active development and equipped the property with an air compressor, a hoist, and a steam-power plant and erected a small wharf and several buildings. The position of the ore body necessitated the sinking of a shaft 100 feet, and at this depth considerable crosscutting and drifting were extended to explore the ore body at this level. A tunnel, started near the shaft, has been driven along the vein for 210 feet, but the results were not encouraging. Operations on this property were suspended during the winter of 1907 and were not renewed in 1908.

Ore bodies.—The ore body is a vein deposit of nearly massive sulphide ore inclosed in a narrow fissure parallel to the stratification of the greenstone schist country rock. The vein is from 1 foot to 3 feet wide and has been exposed for about 250 feet, for which distance it strikes N. 70° W. and dips 70° SW. A tunnel 210 feet long was driven southeastward along the vein and in this tunnel the vein narrows to a thin gouge seam and widens again at several points, its continuation being indicated by the bleached appearance of the country rock. The footwall of the vein is a dark-green schist and appears less altered than the hanging wall, which is a pale-green talcose schist. Grooves caused by slipping were observed on both the footwall and the hanging wall. These grooves pitch 50° NW., and the ore shoots most likely follow this direction. In the vein itself occasional slickensides were observed, indicating movement since the deposition of the ore. The vein is cut by dikes of diabase, 2 to 4 feet wide, striking N. 10° E. and dipping 70° NW., nearly at right angles to the prevailing rock structure. The ore is principally pyrite, containing chalcopyrite associated with some quartz and calcite as gangue minerals. Besides the small quantity of copper, the ore carries, as reported, gold and silver amounting to about $3 per ton. Explorations at other points on these claims may reveal similar vein deposits.

COPPER CITY MINE.

Situation and development.—The Copper City mine, also known as the Red Wing group, consisting of four claims, is near tidewater on the east side of Hetta Inlet, 7 miles south of Copper Harbor. This property has been a copper producer in a small way ever since operations first began, in 1903, the ore being sacked and shipped to the Tacoma smelter. The developments up to 1908 have been confined to the Red Wing claim, where the vein deposit has been opened by an inclined shaft 120 feet in depth. From this shaft two levels, 50 and 100 feet, respectively, below the surface have been driven. The 100-foot drift is the working level and this has been carried along the vein for 200 feet north and 50 feet south of the shaft. At a point on the level 75 feet north of the shaft a 60-foot winze has been sunk and from this a drift 50 feet long has been run. Most of the ore above the 100-foot level has been mined, and it is proposed to sink the shaft an additional 100 feet and open up a 200-foot level.

Ore body.—The ore body, a vein deposit of nearly massive sulphide ore, is inclosed in a slate-greenstone country rock parallel to the bedding and corresponds in general character to the ore body at the Corbin mine already described. The country rock grades from a black slate or siliceous schist to an amphibole schist or altered greenstone, the general strike being N. 20° E. and the dip 60° NW. These schists and also the vein deposits are crosscut by several diabase dikes, 1 foot to 5 feet wide, which strike about N. 30° W. These dikes were intruded after the main ore deposition, but subsequent mineralization has deposited small amounts of mineral in veinlets in them, and the ore bodies, where crosscut, usually continue along the same line of strike on opposite sides of these intrusives. The vein as exposed in the shaft varies from 6 inches to 4 feet in width, narrowing to a gouge seam at a depth of 100 feet. At this level the vein appeared to be displaced for a short distance toward the footwall side, where it was again found, and on it a 60-foot winze was sunk, in which the vein was reported to be wider. Similar but smaller veins, trending parallel to the main vein, have been exposed by surface cuts and trenches at other points on the property, but none of these have been developed.

The ore is composed essentially of chalcopyrite, pyrite, sphalerite, and rarely hematite (specularite), associated with quartz, calcite, and epidote as gangue minerals. Surface oxidation has altered the chalcopyrite in places to limonite and cuprite, and along joint cracks in the country rock malachite and small films of native copper were observed. In addition to copper each ton of the ore contains gold amounting to $3 to $6 and silver amounting to $1 to $3, as well as 6 to 9 per cent of zinc.

PROSPECTS ON GOULD ISLAND.

Gould Island, which lies south and east of Sulzer, is about 2 miles long and less than 1 mile wide. It is composed essentially of limestone, siliceous schists, and slate intruded by a diorite mass which occupies the eastern portion of the island. The prospects are at the southwest end of the island. The ore, which consists of galena, sphalerite, and chalcopyrite, occupies small veinlets, and is finely disseminated in a belt of siliceous limestone 30 feet wide, striking east and west, and dipping steeply north. Associated with the ore are calcite, quartz, garnet, epidote, and large amounts of wollastonite, which occurs in the adjacent limestone in radiating masses. A tunnel 70 feet long, driven along the footwall of this mineralized belt, where it is in contact with slate, disclosed scattered occurrences of ore. Just north of the tunnel is an open cut and a shaft, 10 feet deep, exposing mineralized rock of the same character. About 300 feet east of these workings is another open cut and a pit, 10 feet deep, on the same belt. The ore exposed on these claims at the time of the writer's examination, in 1908, was small in amount and of low grade.

PROSPECTS AT HEAD OF COPPER HARBOR.

The prospects at the head of Copper Harbor, indicated on Plate II (p. 28), except the Paris vein, are all contact-metamorphic deposits and lie adjacent to the same granodiorite batholith that is exposed on the Copper Mountain and Jumbo groups. On none of these claims did the developments up to 1908 exceed the assessment work required. On the Paris group of claims, at an elevation of 300 feet, about half a mile from the beach, a tunnel 115 feet long has been driven along a small quartz vein, striking northeastward and carrying a low content of copper and gold. The country rock is a banded quartzite striking N. 40° W. and dipping 40°–60° SW. The Gould group, which lies north of Reynolds Creek, half a mile from Copper Harbor, at an elevation of 300 feet, is located along the contact of the diorite with quartzite, which at this point strikes S. 20° E. A 50-foot tunnel crosses the contact rock and enters the granite, in which also small amounts of chalcopyrite and pyrrhotite are scattered near the contact in fine particles. A 40-foot shaft at the mouth of the tunnel exposes the mineralized garnet-epidote rock, showing a banded structure striking parallel with the contact and dipping 60° SW. About a mile northeast of the Gould group and at an elevation of 100 feet is the Russian Bear claim, and adjoining this on the north is the Texas claim, at an elevation of 1,450 feet. The contact-metamorphic deposits on both these claims flank the western slope of the granodiorite batholith, and the developments consist mainly of open cuts and trenches, in which only small masses of ore have been exposed.

PROSPECTS ON HETTA MOUNTAIN.

Hetta Mountain, which lies southeast of Copper Harbor, is made up essentially of limestone and quartzite, its northern slope, as indicated on Plate V, being bordered by the granodiorite intrusive. Two claims have been located on contact deposits along the intrusive contact about a mile from Copper Harbor, at an elevation of 900 feet. In 1908 the ore bodies had been prospected by three tunnels, one 20 feet, one 25 feet, and one 30 feet in length, and several open cuts in which small masses of chalcopyrite and pyrrhotite are exposed in the garnet-epidote contact rock. The quartz schist country rock on the south, which forms the hanging wall of the deposits, strikes east and west, has a nearly vertical dip, and is intersected by granitic and pegmatitic dikes.

In a gulch at an elevation of 1,380 feet another prospect is located on a vein deposit consisting of garnet with some epidote and sulphide ores in the siliceous schists. Here, at a point where a small mass of chalcopyrite ore is exposed, a tunnel 30 feet long has been driven on the vein. On the ridge of Hetta Mountain the quartzites alternate with beds of limestone which strike N. 80° E., and which are intruded here and there by masses of granodiorite. Along the contact of one of these dikes on the north slope of the ridge, at an elevation of 2,480 feet, there is a contact-metamorphic deposit which contains both the sulphide and the carbonate of copper. A tunnel 15 feet long and considerable stripping constitute the developments and expose small masses of the copper ore in a garnet gangue. Southeast of this prospect, on the opposite side of the ridge, at an elevation of 2,500 feet, an iron capping has been explored by trenches in which also small amounts of copper ore are exposed.

KASAAN PENINSULA.

TOPOGRAPHY.

MAIN FEATURES.

Kasaan Peninsula is a promontory on the east side of Prince of Wales Island that includes about 60 square miles and lies between 132° 5′ and 132° 35′ W. longitude and 55° 25′ and 55° 40′ N. latitude. (See Pl. XIII, in pocket.) Seen from a steamer on Clarence Strait the peninsula appears to be an island, whose summits are highest near its central part and diminish in height toward the north and south. A neck of low land between the head of Kasaan Bay and the south end of Thorne Bay connects the peninsula with Prince of Wales Island. This low pass appears to represent the continuation of a valley, from 8 to 10 miles wide, which is tributary to the north branch of Thorne Bay and extends northwestward through the center of Prince of Wales Island. Kasaan Bay, which is 18 miles long and 1½ to 4 miles wide, occupies the south end of this valley. In the northward extension of this valley and on the low pass south of Thorne Bay there are many small lakes and morainal deposits, which will be mentioned later.

The highest point on the peninsula is the top of Kasaan Mountain (Pl. XIV, *A*), which has an altitude of 2,840 feet. The other mountains average about 2,000 feet in height and their slopes are deeply dissected by small valleys and by narrow steep-sided gulches.

LEVELS OF EROSION.

On Kasaan Peninsula there are many flat areas, some of them containing small lakes, and the mountain slopes themselves are interrupted by benches or terraces (Pl. XIV, *C* and *D*), which occur at different elevations and apparently at rather regular intervals above sea level. These benches represent levels of erosion.

The lowest bench level is indicated by a series of flats or forelands at a height of about 50 feet above sea level. (See Pl. XIV, *D*). Forelands at this height are especially prominent at the head of Kasaan Bay and on the adjacent islands. Along the northern shore of the peninsula and in Tolstoi Bay a higher level of erosion, which seems persistent at 100 to 150 feet on many parts of the peninsula, is marked by wide flats in the valleys, some of which are occupied by small lakes. Such flats occur just north of Grindall Point; on the hills just north of Kasaan; northeast of the Haida mine, where the flat is covered by a lake; on both the east and west slopes of Tolstoi Bay; and southwest of Thorne Bay, where there are two large lakes.

Still higher, at an elevation of 250 to 300 feet, a level of erosion is represented by a flat, occupied by a lake, at the head of Poor Mans Creek, on the divide toward Tolstoi Bay; by flats north of the Alarm claim, on which there are several lakes; and by several areas occupied by lakes northeast of the Haida mine. The surface of the lake just east of Lake Three, at the head of Kasaan Bay, and that of the lake below the Goodro mine are also at this elevation.

The next or fourth series of benches and flats are prominent at an elevation of about 500 feet above sea level. At this level also there are lakes, from which small streams flow down through gulchlike valleys to lower levels. At this altitude there are terraces along the north slope of the southwest half of the peninsula, flats south of Hadley, a low pass across the peninsula southwest of Lyman Anchorage, and the lakes and flats on the divide from Windfall Harbor to Tolstoi Bay and east of the It mine. Most of the summits of the hills north of the It mine and adjacent to the Salt chucks at the head of Kasaan Bay are at an elevation of about 500 feet.

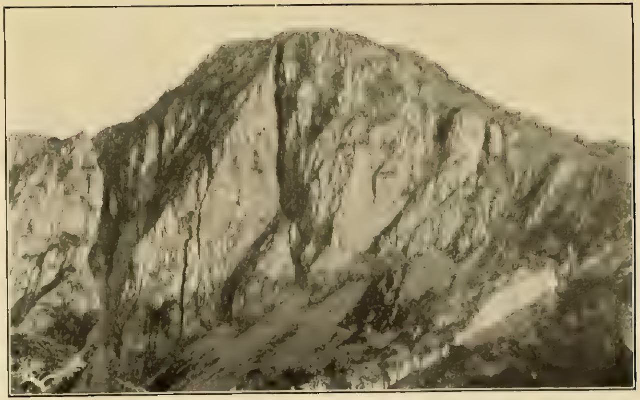
Higher levels of erosion are indicated at elevations of 1,100 and 1,300 feet by lakes and flats in the central portion of the southeast half of the peninsula, by flats that are in part occupied by lakes on Mount Andrew and on the mountain just west of Lyman Anchorage, and at the head of a branch of Tolstoi River. Other lakes at an altitude of about 1,500 feet north of Grindall Point Mountains and north of Kasaan Mountain may mark a higher erosion level.

The highest relatively level areas stand at an altitude of about 1,850 feet, on the Grindall Point Mountains, where there are also small lakes, though they are not shown on the map; also on the ridge southeast of Kasaan Mountain and on Tolstoi Mountain.

GLACIATION.

The mountain mass of Kasaan Peninsula exhibits characteristic glaciated topography. That the entire peninsula was at one time overridden by ice streams is evident from the glacial erratics which lie on the highest summits, the moraine deposits which occur on the lower levels, and the many basins which stand at various elevations on the mountain slopes and are now occupied by lakes. (See Pl. XIV, *C*.) During the period in which this area lay beneath the

A. VIEW SOUTHEASTWARD FROM KASAAN MOUNTAIN.



B. NORTH SIDE OF KASAAN MOUNTAIN.

C. TOPOGRAPHY ON SUMMIT OF GRINDALL MOUNTAIN.

Showing small lake basins and scrub pine above timber line.

D. FORELANDS ALONG NORTHEAST SIDE OF KASAAN BAY.

Mountains on Kasaan Peninsula in background. View taken from point at entrance to Salt Chuck at head of Kasaan Bay

ice many of the minor topographic features, such as the earlier erosion level, were partly destroyed. Some of the valleys were more deeply eroded, lake basins were formed, and wide areas of glacial silt and débris were laid down. This section of the ice stream is well represented in the northern extension of the valley of Kasaan Bay, which is occupied by a chain of connecting lakes, on the sides of which thick beds of glacial clay and débris have been exposed by subsequent stream erosion. This valley probably represents a preglacial river floor, and only the lake basins and minor physiographic features can be attributed to ice erosion.

Erosive action subsequent to the ice period has formed the gulches and ravines which are everywhere prominent on the mountain slopes.

Another noteworthy feature of Kasaan Peninsula is its precipitous southwest slope, which is much steeper than that on the northeast. This difference may be due to the fact that the ice stream remained longer in the valley of Kasaan Bay than in that of Clarence Strait, the action of the ice tending to deepen the valley and at the same time to protect the mountain slopes from surface erosion.

FORESTS.

Kasaan Peninsula is densely forested with spruce and hemlock, principally hemlock, which extends to elevations of 1,500 to 1,800 feet. (See Pl. XIV, *C*.) The timber, especially that on the southwest side, toward Grindall Point, is large and straight. The mountain side is steep down to salt water, so that the timber is easily accessible. The mountain summits and ridges above timber line are fairly open and bear relatively little vegetation as compared with that of the densely forested lower levels (Pl. XIV, *D*), groups of scrubby pine and juniper and a low berry bush being the principal plants found.

Prince of Wales Island was included in the Tongass National Forest, but in 1908 that portion of Kasaan Peninsula which lies south of the Hole in the Wall (the boundary line is indicated on Pl. XIII) was taken out of the national forest.

GEOLOGY.

GENERAL FEATURES.

The geology of Kasaan Peninsula displays strikingly the phenomena of igneous intrusion and contact metamorphism. The geologic problems are numerous, but in this report it is possible to consider only the questions that directly bear on the occurrence of ore.

The relations of the geology of the peninsula to that of the Ketchikan mining district have been already described (pp. 16–28). The following discussion will be confined to the stratified rocks, which comprise those of sedimentary and volcanic origin; the intrusive rocks, which apparently underlie the peninsula and consist essentially of granitic and porphyritic rocks; and the ore deposits.

The stratified rocks are of interest to the miner because they determine the character and composition of the ore bodies. The intrusive rocks are of even greater interest because they are believed to be the original source of the ores. As the principal ore deposits are found at or near contacts between certain intrusive and stratified rocks, it is desirable to determine the particular intrusive or intruded rocks with which the ore deposits are most commonly associated.

THE GEOLOGIC MAP.

On the geologic map (Pl. XV, in pocket) an attempt has been made to show the distribution of the stratified and intrusive rocks and to indicate the location of the principal known ore bodies. In the field much difficulty was encountered in determining the geologic boundaries and in recognizing the various geologic formations, some of which are remarkably similar. The mountain sides are heavily timbered and the low levels and flats are covered with a dense growth of vegetation, so that exposures of bedrock are rare and are found principally in the stream gulches and at points along the shore. These meager rock exposures afford the only means of indicating the distribution of the various rock formations in the areas that are covered with vegetation and talus. The geologic sections that accompany the map and show the underground structure of the rock formations are based entirely on inferences from surface observation, except in places where the structure was revealed by mine workings. Future detailed geologic mapping and mining will doubtless disclose many errors in this map, yet the writer believes that it shows with fair accuracy the general distribution of the rock formations and that it may therefore be of use to the miner and to the prospector.

STRATIFIED ROCKS.

CHARACTER AND RELATIONS.

The stratified rocks are principally tuffaceous graywackes interstratified with quartzites, conglomerates, and some limestones. These sedimentary deposits comprise a conformable series of beds several thousand feet thick, all probably of Devonian age. They occur principally in the northern part of the peninsula and have been generally altered by regional and contact metamorphism. It was not possible in the field to subdivide these sediments stratigraphically, so that in this discussion and on the accompanying map they are considered only as to their lithology. Two lithologic types have been recognized in the mapping—(1) a series of clastic rocks, including graywacke, quartzites, and conglomerates, and (2) a series of limestones. The limestones are of the greater economic importance because of the influence they have had on the occurrence of the copper deposits.

Nearly two-thirds of Kasaan Peninsula is occupied by clastic rocks, which in large part consist of a series of metamorphosed sediments, usually epidotized and containing crystals of amphibole or pyroxene. In texture these beds range from fine-grained compact rocks, such as quartzites and graywackes, to coarse conglomerates. As these sedimentary rocks are composed of igneous material, and as they have been greatly altered, they closely resemble massive igneous rocks, though in most places their clastic texture may be recognized, especially on weathered surfaces.

The term Kasaan greenstone was applied to these beds by Brooks in his report on the Ketchikan district in 1901,[1] but detailed study has shown that they are graywackes containing in certain places tuffaceous material. Interstratified with these rocks are narrow beds of limestone, which are entirely recrystallized and contain no traces of organic remains. The relation of these limestone beds to the fossiliferous beds on Long Island, in Kasaan Bay, 1 mile southwest of Kasaan Peninsula, is important and will be discussed later. The stratigraphic succession of these sedimentary rocks is difficult to determine, as the beds are nearly vertical in dip and structurally appear to lie in the form of a synclinorium.

The rocks of this series are described separately, and these descriptions are followed by a discussion of their age and structural features.

GRAYWACKE.

Graywacke is a general term that was used in the field to designate certain obscurely bedded, in places much altered, greenish rocks, which range in texture from distinctly conglomeratic to aphanitic. Some of the finer-grained graywackes can with difficulty be distinguished from igneous rocks. The results of the field study led to the inference that the graywackes consist largely of igneous material worked over mechanically but not greatly decomposed before deposition, and this inference is confirmed by microscopic study. Since their deposition, however, they have been in places greatly changed by shearing, brecciation, and the development of secondary minerals. Some of the most characteristic specimens collected were selected for detailed study. The order in which they are described follows generally their increasing fineness and metamorphism. The degree of metamorphism necessary to convert a certain rock into a graywacke has not been determined or defined, but for those specimens studied in thin section in which metamorphism had gone far enough to be readily detected the field name graywacke has been retained. The microscopic examinations and descriptions are the work of H. E. Merwin.

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[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska, with an introductory sketch of the geology of southeastern Alaska: U. S. Geol. Survey Prof. Paper 1, pp. 49–50, 1902.

Specimen 129. Graywacke (conglomeratic). The broken surface of this rock has the appearance of an augite lamprophyre; the weathered surface shows bedding and pebbles. In the slide two kinds of pebbles can be made out, one of graywacke, consisting of fragments of augite, hornblende, and feldspar in a dusty chloritic matrix; the other of porphyry, containing large crystals of fresh augite with decomposed feldspar in a groundmass which is chiefly chloritic. Besides pebbles there are angular fragments of porphyry and of minerals derived from porphyry. This angular material and dustlike particles and chlorite form the matrix of the rock.

Specimen 195. Graywacke (conglomerate). In the hand specimens pebbles of porphyritic rocks, the largest several centimeters in diameter, can be distinguished, but their outlines are not clear. Some of these pebbles contain large crystals of hornblende. The thin sections show that the pebbles represent at least five different porphyritic rocks. The matrix consists of fragments of hornblende and feldspar, which are partly chloritized and partly recrystallized as hornblende and epidote. Borders of the secondary hornblende have formed around the original large fragments of hornblende. The rock contains minute veins of secondary hornblende, calcite, epidote, and zoisite.

Specimen 188. Tuff. Megascopically the rock has the appearance of a fine-grained altered hornblende lamprophyre, which contains scattered angular inclusions of a medium-grained leucocratic rock. When moistened the dark parts of the rock also seem to have inclusions. Viewed microscopically the fragmental material appears more angular than that in the rocks already described, and includes abundant broken crystals of hornblende and augite. Much of the matrix is too fine grained for determination. The material as a whole seems to be like that of broken-down but not greatly altered porphyry.

Specimen 196. Graywacke. In the hand specimen this rock looks like basalt, containing minute prisms of hornblende in a much finer grained matrix. Slight magnification of the slide, however, shows clearly the fragmental character of the constituents. Secondary hornblende appears in the matrix and in veins. Epidote accompanies the hornblende in some veins. White mica is the chief alteration product of the feldspar.

Specimen 424. Graywacke. This rock is dark greenish gray mottled with dark red, having a brecciated appearance. The microscope shows that the red patches are fragments of acid porphyries in which phenocrysts of feldspar are contained in a groundmass that is now almost entirely calcite and chlorite. The matrix of the graywacke consists of fragments of feldspar cemented by calcite and chlorite.

Specimen 351. Graywacke. A fresh surface of the rock is dark greenish. The only distinguishable structures are irregular cleavages of hornblende and light aphanitic rounded or subangular patches. A weathered surface is light colored and chalky, with distinct aphanitic patches, the largest 3 centimeters in diameter. Under the microscope the aphanitic material is seen to be aplite, mostly orthoclase, surrounded by hornblende in ragged crystals and granular orthoclase and plagioclase. Epidote and magnetite are abundant. Much of the hornblende appears to be secondary, for the borders of the fragments of aplite are penetrated by the minerals of the matrix.

QUARTZITE.

Prominent beds of quartzite are interstratified with the graywacke. They are of aphanitic texture, are light gray to brown in color, and are highly indurated and brittle. The quartzite at most places contains many cleavage cracks and has a banded structure, which is usually parallel to the main structural lines of the complex. The microscope shows that the quartzite is made up essentially of quartz and a large percentage of feldspar. The rock is an extremely fine textured phase of graywacke, the conglomerates representing the coarse phase.

CONGLOMERATE.

The conglomerate is made up principally of fine to coarse, rounded, waterworn pebbles, though some of the beds contain cobbles and even bowlders. The matrix or cement of this conglomerate is essentially silica and calcite and in certain beds the calcite is most abundant. The pebbles and cobbles are of chert and limestone, those of chert being the more numerous. (See Pl. XVI, *D*.)

LIMESTONE.

Beds of limestone are intercalated with the graywacke and conglomerate. These beds are entirely recrystallized and contain no traces of organic remains. They are of interest because of their association with and relation to the ore deposits, and are indicated separately on the geologic map. They range in thickness from less than 100 to about 600 feet, strike northwestward, and dip to the northeast or to the southwest. At some places the beds are wrinkled and irregularly folded; at others they are brecciated. Dark-colored siliceous beds, from a fraction of an inch to a few inches thick, are interstratified with certain of the limestones, and at some places epidote and garnet have been introduced into the limestones along bedding planes and fractures. (See Pl. XVI, *C*.)

FOSSILIFEROUS LIMESTONES ON LONG ISLAND.

Beds of limestone conformably underlain by feldspathic sandstones and conglomerates occur on Long Island, which is in the central part of Kasaan Bay and lies a mile southwest of Kasaan Peninsula. Interstratified with these limestone beds near their contact with the underlying rocks are narrow beds of sandstone and conglomerate, most of the pebbles in the conglomerate being of porphyry. The limestone beds themselves contain abundant fossils, of Devonian age.

Collections were first made at this locality by A. H. Brooks in 1901. In 1905 a more complete collection was made by E. M. Kindle, who submitted the following report:[1]

> Blue limestones form much of the surface outcrops on a group of small, low islands near the middle of Kasaan Bay, of which Long Island is the largest. On Round Island the limestones are not greatly metamorphosed, but have occupied a zone of vigorous deformational activity. The island affords an uninterrupted outcrop of the limestones entirely around its shore line. These outcrops are of particular interest as illustrating in a small area the complex character of the deformation in this region. The beds are everywhere inclined at a high angle, usually about 90°. On the north and east sides of the island the strike is within a few degrees of due north. From nearly due north the strike swings around abruptly to N. 80° E. on the west side of the island. The exposures on the west side show the sharp elbow which the nearly vertical strata make in changing from a northerly to an easterly strike. The limestone on Round Island is shown by its fossils to be of the same age as the upper beds on Long Island, which lie a few hundred yards southeast.
>
> On Long Island, which has a length of about 2 miles and an average width of less than one-half mile, the limestones show a less degree of deformation than those of Round Island. The flexures have comparatively gentle dips, amounting in parts of the southeastern portion of the island to only 5° or 10°. In the western part of the island, however, the dip rises to 90°. The strike, as on Round Island, varies greatly.
>
> A section along the south side of Long Island from the east end to Salt Pond shows the following series of beds
>
> *Section 12, Long Island.*

	Feet.
c. Hard dark-gray limestone, slightly darker than the preceding	270
b. Hard blue fine-grained limestone, fracturing easily in any direction	200
a. Buff or cream-colored feldspathic sandstone underlying the limestones	90
	560

> The two divisions of the limestone series are conformable, and the upper and lower portions are very similar in lithologic character. Analyses of the upper and lower portions of the limestone series show them to be very similar in chemical composition, one carrying 96.11 per cent, the other 97.50 per cent of lime.
>
> Aside from the faunal differences, which are quite marked, there are no very evident reasons for making two divisions of the limestones.

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[1] Wright, F. E. and C. W., The Ketchikan and Wrangell mining districts, Alaska: U. S. Geol. Survey Bull. 347, pp. 47–49, 1908. See also Kindle, E. M., Notes on the Paleozoic faunas and stratigraphy of southeastern Alaska: Jour. Geology, vol. 15, pp. 324–327, 1907.

Fauna.—The character of the fauna in the lower section (*b*) of the limestone series is indicated by the following list:

Stictopora sp.
Cladopora sp.
Spirifer cf. sulcatus Hisinger.
Sanguinolites sp.
Cardiola sp.
Hercynella nobilis Barr.
Hercynella bohemica Barr.
Holopea sp.
Murchisonia angulata Phillips.
Murchisonia sp. 1.
Murchisonia sp. 2.
Planitrochus cf. amicus.
Loxonema sp.
Holopella sp.
Trochonema sp.
Euomphalopteris? sp.
Operculum.
Beyrichia? sp.
Leperditia sp.
Orthoceras sp.

The occurrence of the genus Hercynella in this fauna is of considerable interest, since it has not been found heretofore in America. *H. bohemica* occurs in the Lower Devonian of the Ural Mountains. Both *H. bohemica* and *H. nobilis* are present in étage F of Barrande's Bohemian section. Their presence in the fauna at Long Island indicates that the latter is much more closely related to the European and Asiatic than to the American faunas outside of Alaska. This lower fauna at Long Island represents the lowest Devonian horizon which has been found in Alaska.

In the upper portion of the higher limestone (*c*) the following fauna is found:

Favosites cf. radiciformis Rom.
Cyathophyllum sp.
Orthophyllum? sp.
Zaphrentis sp.
Calceola cf. sandalina.
Syringopora sp.
Lingula cf. bohemica.
Atrypa reticularis Linn.
Atrypa hystrix Hall.
Gypidula opatus (Barr).
Gypidula cf. intervenicus (Barr).
Meristella cf. barrisi Barr.
Stropheodonta stephani (Barr).
Spirifer sp.
Spirifer hians Bich.?
Spirifer thetidis Barr.
Spirifer subcomprimatus Tsch.
Spirifer sp.
Spirifer indeferens Barr.
Spirifer sp.
Reticularia? sp.
Rhynchonella cf. amalthea Barr.
Rhynchonella livonica Buch.
Pugnax sp.
Dalmanella occlusa Barr.
Schizophora macfarlani Meek?
Schizophora striatula Schloth.
Streptorhynchus sp.
Stropheodonta comitans Barr.
Camarotœchia? sp.
Cypricardinia? sp.
Conocardium cf. bohemicum Barr.
Conocardium sp.
Lucinia cf. proavia Goldf.
Leptodesma sp.
Mytilarca sp.
Nuculites sp.
Telinopsis sp.
Holopella? sp.
Loxonema? sp.
Murchisonia sp. 2.
Murchisonia sp. 1.
Naticopsis sp.
Oriostoma sp.
Oriostoma princeps var. Oehlert.
Euomphalus cf. planorbis D'Arch. and Vern.
Tremanotus cf. fortis Barr.
Tentaculites sp.
Ooceras sp.
Gomphoceras? sp.
Orthoceras sp.
Cytherella? sp.
Entomis pelagica Barr.
Lepterditia sp.
Cyphaspis sp.
Proetus sp.
Proetus cf. romanooski Tsch.

In place of the gastropods, which are the dominant forms in the lower horizon, the brachiopods, are the predominant group of this fauna. The Hercynellas, which are abundant at five horizons in the lower beds, appear to be entirely absent. The upper fauna, however, agrees with the lower in its foreign affiliations. In it occurs the peculiar coral, Calceola, very common in the Middle Devonian of Europe. Several specimens among the brachiopods are either identical with or have their nearest analogy in European species. The fauna represents a Middle Devonian or late Lower Devonian horizon.

The lowest 40 feet of division *c* of the Long Island section furnished a fauna differing but slightly from that of the upper part. The following list indicates its character:

Cladopora?
Cyathophyllum sp.
Camarotœchia sp.
Meristella cf. ceres Barr.
Spirifer sp.
Spirifer cf. thetidis Barr.
Spirifer cf. cheiropteryx.
Stropheodonta comitans Barr.
Orthonota sp.
Schizodus sp.
Conocardium cf. bohemicum Barr.
Euomphalus planorbis D'Arch. and Vern.
Oriostoma princeps var. Oehlert.
Tentaculites.
Cyrtoceras sp.
Orthoceras sp.
Proetus cf. romanooski Tsch.

The stratigraphic relations of limestones of Long Island to the geologic horizons represented on the adjacent shore of Kasaan Bay can not be determined because of their topographic isolation.

These limestones are white to gray in color and are noncrystalline. The change from the sandstone to the limestone is abrupt and the limestone occurs only in the upper part of the series. The beds are in general slightly folded, several changes from anticline to syncline having been noted on the shore of the island, the anticlines forming the bays and the synclines the points. Some faults were observed. At a point on the southeast end of the island the limestone lies in contact with sandstone and though the strike was the same the dip was different, suggesting an unconformity. At other points, however, the conformity of the limestones and sandstones was evident.

The structure of the sedimentary rocks exposed on Long Island is of interest because it shows two systems of folding, an older system of small folds with a northeasterly strike and flat dips to the northwest and southeast, and a later system of broader folds which trend northwest and are parallel to the main structural lines of the Coast Range.

AGE OF THE SEDIMENTS.

Though no fossils were found in the limestones on Kasaan Peninsula, the rocks are regarded as Lower Devonian because of the occurrence of fossiliferous limestones on Long Island interstratified with sandstones and conglomerates. Graywackes and conglomerates which correspond somewhat more closely to those of metamorphosed sediments on Kasaan Peninsula are found on the northwest side of Prince of Wales Island and these lie between limestone beds carrying Lower Devonian fossils.

STRUCTURE.

The structure of the stratified rocks on Kasaan Peninsula is that of a closely folded synclinorium in which the beds in general strike northwest and dip northeast. This structure, however, is interrupted locally by masses of intrusive rock, and where these occur the bedding planes of the stratified rocks are usually parallel with the line of contact of the intrusive mass.

Two prominent joint systems were noted on the peninsula, one striking N. 15°–25° E. and dipping 60°–80° SE., and the other striking N. 50°–70° W. and dipping steeply to the northeast. As these joint cracks traverse the ore bodies and country rock alike they were doubtless developed subsequent to ore deposition, and the fact that most of the basalt dikes follow the prominent directions of jointing indicates that the jointing occurred before the basaltic intrusions. Fault planes and gouge seams were noted in the mine workings, and the ore deposits and the dike rocks have here and there been displaced along these planes. The amount of displacement, however, seldom exceeds a few feet.

DETAILS OF OCCURRENCE.

The rocks exposed along the shore north of Hadley are brown to green quartzites containing some amphibole in finely scattered crystals, highly indurated graywackes containing large hornblende crystals embedded in a fine clastic feldspathic groundmass, and gray to green limestones which are locally cherty in appearance. At some places the limestone beds may be regarded as conglomerates with a calcareous groundmass; at others their groundmass is a dark siliceous material. Rounded pebbles of quartzite and white fine-grained limestone are contained in the conglomerate, and in spots the rock is impregnated with epidote and the groundmass is apparently recrystallized. At Lyman Anchorage the graywacke beds are of a fine granular texture, showing microscopic crystals of amphibole, and in places the rock is finely fractured, the cracks being filled with quartz and epidote, and portions of the rock are impregnated with epidote, which gives it a light-green color.

Farther north, at Windfall Harbor, there are beds of argillaceous quartzite altered to phyllite and biotite schist and hornfels, the alteration being partly due to adjacent intrusive masses. At Palmer Cove the graywackes are much altered and epidotized and intruded by granitic rocks. Veinlets of feldspar, quartz, and epidote are prominent along jointing planes in these rocks.

The rocks exposed on the south arm of Thorne Bay consist largely of fine to coarse conglomerates, which are in places much brecciated, so that their sedimentary nature is disguised. The pebbles and cobbles of these conglomerates consist of graywackes, usually somewhat epidotized and containing hornblende crystals, and of porphyry, chert, and limestone. The rocks at this locality are somewhat less metamorphosed than at other points nearer the intrusive masses.

The graywackes along Tolstoi Creek are more brownish and the conglomerates contain brownish fragments of a slaty rock. These beds are also less altered than the graywackes near the intrusive contacts and are not impregnated with epidote, feldspar, and quartz. The limestones also show less effect of metamorphic action.

The rocks exposed on the west side of the peninsula are essentially graywacke and occasional beds of conglomerate, striking in general northwestward and dipping northeastward. Many of the exposures of the graywacke resemble those of a diorite intrusive mass because of their content of hornblende crystals. Their clastic texture and sedimentary origin were, however, evident on weathered surfaces, especially where the graywacke graded into the coarser phase or conglomerate, and they contained limestone pebbles.

At the Rush & Brown mine the rocks grade from a quartzite of banded aphanitic texture to a graywacke and coarse conglomerate. The conglomerate is highly epidotized and the matrix contains hornblende pyrite. (See Pl. XVI, *D*.) Most of the pebbles are of graywacke, porphyry, and limestone. The graywacke is also somewhat epidotized, especially along cracks. At the Venus claim, 1 mile south of the Rush & Brown mine, beds of conglomerate are interstratified with banded slates and graywackes. The conglomerate contains cobbles of quartzite, slate, limestone, and porphyritic rocks with quartz phenocrysts. The graywackes in general show a slight development of hornblende crystals and contain numerous slaty fragments, though in certain areas where metamorphism was apparently greater the slaty fragments are almost absent and the crystals of hornblende are more abundant. These conditions suggest intense metasomatic action in these somewhat porous rock beds, though the development of schistosity which usually accompanies such metasomatic action is lacking, probably because of the resistance of the rock to differential pressure.

At the Copper Center mine the graywacke is much epidotized and contains large crystals of hornblende associated with chalcopyrite. At the Charles prospect the graywacke and conglomerate grade into the contact rock, and masses of conglomerate are surrounded by the contact rock. A similar alteration of the graywacke is evident at the Brown & Metzdorf prospect, where an ore deposit in the contact rock occurs between a limestone bed and graywacke, showing a replacement of both graywacke and limestone. In all these places the rocks are highly metamorphosed, contain much hornblende, and are impregnated with epidote. The occurrences of contact rock at these prospects indicate the proximity of intrusive rock, which was not exposed on the surface, though its presence is indicated on the map in adjacent areas.

The alteration of the limestone is especially evident along the shore just north of Kasaan, where it is much wrinkled, recrystallized, and has a banded structure. The bands are composed of quartz and epidote and veinlets of epidote and garnet, which protrude on weathered surfaces between the bedding planes, showing still further the alteration of the rocks by mineralizing solutions.

INTRUSIVE ROCKS.

OCCURRENCE AND CHARACTER.

The intrusive rocks that apparently underlie Kasaan Peninsula occupy about one-third of its surface. They invade all the sedimentary strata and are therefore more recent than these stratified rocks. (See map, Pl. XV.) They vary in composition from acidic granite and pegmatite to basic diorite and basalt, and in texture from coarse granular to fine porphyritic rocks. They occur in the form of huge intrusive batholiths, many miles in width, and in dikes, the smallest less than a foot wide. The larger masses are longest from northwest to southeast, parallel with the lines of folding of the stratified rocks. The principal intrusive rock is a diorite, which forms the entire southern part of the peninsula and occupies large areas in its central and northwestern parts. No intrusive rocks earlier than the diorites have been recognized in this region.

Pegmatite dikes intrude the diorites and adjacent metamorphic rocks but are not plentiful. In composition they are nearly like the diorites and were probably derived from the same magma. Porphyritic rocks in the form of dikes, some a few hundred feet wide, also invaded the stratified rocks. The most recent intrusives are numerous small basalt and diabase dikes, which crosscut all the rock formations and the ore bodies.

The intrusive bodies, especially the granitic rocks, are of interest to the prospector, for the principal ore deposits lie at the contacts of the intrusive and the country rock. The main intrusive masses on the peninsula are commonly called granites, though they correspond more closely in composition to diorites. Like the intrusives of the Coast Range, however, this granitic rock varies in composition from a granite to a gabbro, including also syenite, though most of it is diorite.

GRANITIC ROCKS.

GENERAL CHARACTER.

The granitic intrusives include diorite, gabbro, syenite, and a little granite. These intrusives differ considerably in mineral composition and probably represent several periods of igneous invasion during one general epoch, though some of the differences can undoubtedly be attributed to segregation of minerals within the igneous magma while it was becoming solidified.

At the contacts of these granitic batholiths with the country rock there are masses of slightly altered and locally sheared diorite surrounded by unaltered diorite. At some places these masses show sharp contacts, though at others the two kinds of rock merge gradually into each other, suggesting a peripheral solidification of the igneous batholith, a fracturing of its outer part, and subsequent injection of molten rock into the interstices. The igneous mass includes, here and there, angular fragments of highly metamorphosed stratified rocks, some of which can be recognized as included metamorphic rock only because parts of them show parallel lines of flakes of biotite, the remainder of the inclusions having been dissolved by the intruding magma. The schist near the contact also includes, along the bedding planes, feldspar, quartz, and other pegmatitic minerals, suggesting a partial replacement of the intruded beds by igneous material.

DIORITE.

The main intrusive rock of Kasaan Peninsula is a quartz-bearing diorite. The quartz is scarcely more than an accessory, generally forming not more than 5 per cent of the mass. Orthoclase appears in about the same amount. Plagioclase, which makes up 50 to 70 per cent of the rock, is basic andesine, ranging chiefly from Ab_3An_2 to Ab_1An_1. The range of the composition of the individual plagioclase crystals is about the same. For this reason zoning is not pronounced. Twinning according to both the albite and the Carlsbad laws is very common in the plagioclase. Hornblende is everywhere present, constituting 10 to 35 per cent of the weight of the rock. It is the common variety; it is pleochroic in various yellow-greens; it is optically negative, showing a large optic axial angle; its maximum extinction angle, measured from the trace of the cleavage, is from 20° to 25°, corresponding to an angle of 15° to 20° on (010); and its indices of refraction are considerably higher than those of other recorded measurements, namely from 1.665 to 1.680, determined by the immersion method. Some facies of the diorite contain about 15 per cent of yellow-brown or orange-brown biotite. The rock contains small amounts of augite, less than 10 per cent. The minor accessories are apatite, titanite, and magnetite.

The mineral composition, summarized from a study of 16 slides made of rock taken from different parts of the peninsula, shows that the rock contains too little quartz and orthoclase and that its plagioclase contains too much lime to justify its classification with the granodiorite that is so common on the Pacific slope of North America. According to Lindgren[1] this granodiorite contains an average of about 23 per cent of quartz, 14 per cent of orthoclase, and 44 per cent of plagioclase (near Ab_2An_1).

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[1] Lindgren, Waldemar, Granodiorite and other intermediate rocks: Am. Jour. Sci., 4th ser., vol. 9, pp. 269–282.

Some of the extreme types of the diorites of Kasaan Peninsula are described below. The numbers refer to slides and specimens in the collection of the United States Geological Survey, the full catalogue designation bearing the prefix "7. C. W."

173. Hornblende diorite, from about 4 miles northwest of Hadley. In hand specimen the rock is seen to consist megascopically of plagioclase, hornblende, quartz, magnetite, pyrite, and titanite in a medium-grained groundmass, the bulk of the crystals being between 1 millimeter and 5 millimeters in diameter.

The microscope shows that the rock contains about 55 per cent of plagioclase (Ab_1An_1), 35 per cent of hornblende, 5 per cent of quartz in poikilitic masses, and 5 per cent of accessory magnetite, apatite, biotite, and titanite. In the main the order of crystallization was plagioclase, magnetite, hornblende, and quartz.

135. Hornblende diorite, from the southeastern point of Kasaan Peninsula. Although this is mainly a medium-grained granitic rock, it appears coarse grained on account of its large content of poikilitic masses of hornblende and plagioclase.

Under the microscope the plagioclase, which makes up 60 to 70 per cent of the rock, is found to be about Ab_3An_2. Hornblende, which forms about 25 per cent of the rock, occurs partly in prisms among the feldspar and partly in poikilitic masses inclosing plagioclase. The prisms of hornblende are much lighter in color than the poikilitic masses. Quartz and microcline are very subordinate constituents.

199. Hornblende diorite of medium-grain granitic texture, from a large intrusive mass in the northern part of the peninsula. In the slide the following minerals are found in about the proportions stated: Basic andesine, 70 per cent; hornblende, 15 to 20 per cent; quartz, 5 to 10 per cent; biotite, 5 per cent; accessories, 3 to 5 per cent. Near the contact this rock (specimen 201a) contains phenocrysts of hornblende and plagioclase, the hornblende in many places having nuclei of corroded augite. Augite is very much more abundant in parts of this diorite that have cooled more rapidly than the main body of the intrusive, and particularly in the diorite porphyries to be described later.

106. Biotite diorite of medium grain, from a point near the central part of the peninsula. It contains about 60 per cent of plagioclase (Ab_3An_2), 5 per cent of orthoclase, and 35 per cent of dark minerals, of which biotite is somewhat more abundant than either of the other two essential constituents, hornblende and augite. Magnetite is intergrown with the augite.

GABBRO.

Near some of its margins the diorite becomes basic and passes into gabbro, the hornblende giving place to augite, and the plagioclase becoming richer in lime. Specimens from the mines and prospects north of Karta Bay illustrate this transition.

411. Augite gabbro lamprophyre. This is a melanocratic, porphyritic, medium to coarse grained rock, containing phenocrysts of augite, the larger bordered with primary hornblende and uralite. Many of the smaller phenocrysts are chloritized on the outside and serpentinized within. The groundmass consists of plagioclase (Ab_2An_3), common hornblende, and biotite. Both hornblende and biotite are in part later than the feldspar. The accessories, which crystallized early, are iron ores, apatite, and titanite.

254. Augite gabbro. In the hand specimen this rock is nearly black, medium or fine grained, granitic, and contains visible augite, magnetite, and biotite.

In the thin section the augite is seen to be hypidiomorphic, the distinctly pleochroic grains constituting about 55 per cent of the rock mass. A strongly pleochroic yellow-brown biotite makes up about 25 per cent of the rock and iron ores, in part later than the pyroxene, form 10 to 15 per cent. The biotite is later than both the augite and the magnetite. The spaces among these minerals are filled with much-altered plagioclase. A rock similar to this (specimen 246), much brecciated and impregnated with bornite and chalcocite, is worked as an ore of copper.

SYENITE.[1]

Most of the syenitic rocks occur in dikes and are of porphyritic texture. They are therefore described under the heading "Porphyritic intrusives" (p. 77). Syenite occurs, however, in batholithic masses, principally as a differentiation product of the dioritic magma. The rock shows a preponderance of soda over potassium, as would be expected in a rock derived from a dioritic magma.

43. Albite syenite, from a dike near the head of Hole in the Wall. This is a fine-grained granitic rock, ranging in color from gray-green to red. Its chief mineral is nearly pure albite showing a maximum extinction angle of 16°. The minor constituents are orthoclase (15 to 20 per cent) and biotite (about 10 per cent). Apatite, titanite, and magnetite are accessories, apatite being especially abundant. Although the texture of the rock is granitic, the biotite was in part the last product of crystallization. The rock contains scattered grains of primary calcite and veinlets of secondary calcite.

116. Albite syenite, from a point 1½ miles southeast of Boggs Landing. This type is a light-greenish aphanitic rock that shows in the thin section a fine-grained granitic texture. About 90 per cent of it is albite having a mean refractive index of about 1.530, showing the presence of about 15 per cent of dissolved orthoclase. The rock contains about 10 per cent of quartz but little or no ferromagnesian minerals. This rock and No. 259 are the most alkalic rocks collected from Kasaan Peninsula.

GRANITE.

A second phase of the differentiated diorite magma consists of rocks rich in both alkali feldspars and quartz. Between these rocks and the highly alkalic rocks previously described there are transitional forms, such as the first of the types described below. The more quartzose rocks are in general later and smaller in bulk than the highly feldspathic rocks.

64. Soda granite, from one of the longest granite masses, about 4 miles south of Hadley. This rock is light greenish gray, is medium grained, and consists of visible quartz, plagioclase, and biotite.

In the thin section the proportions of the minerals are seen to be about as follows: Albite, 70 per cent; quartz, 20 per cent; biotite, 10 per cent. The composition of the albite is about $Ab_{15}An_1$, as shown by its refractive index and extinction angle. The accessory minerals are apatite and magnetite.

396. Soda granite, from a dike north of Karta Bay. A light greenish-gray and medium-grained granitic rock. The minerals distinguishable in the hand specimen are quartz, plagioclase, chlorite, epidote, magnetite, and pyrite.

In the thin section the quartz (25 to 30 per cent) is mainly interstitial. The plagioclase has the optic properties of nearly pure albite. These two minerals make up about 98 per cent of the rock. The chlorite is derived from biotite, and epidote has come from the small amount of lime-bearing plagioclase.

39. A medium to coarse grained red granite from a point 1 mile north of Hadley, consisting almost exclusively of light-colored constituents, perthitic orthoclase, and quartz in about equal amounts. The dark constituent is biotite. This is the most acidic intrusive rock collected from the peninsula.

DETAILS OF OCCURRENCE.

The granitic intrusives which compose Grindall Island, at the southeast end of Kasaan Peninsula, are much segregated and fractured. The segregations are essentially masses of basic hornblende locally showing radiating crystals of hornblende a few inches in length. In places the rock grades from coarse-grained to fine-grained diorite within a short space and at other places it appears to have been fractured and the fractures, most of them rather wide, filled with diorite of fine or coarse texture. At certain points a gneissoid banding or flow structure was noted in the intrusive mass and between the bands are irregular masses of a coarse basic

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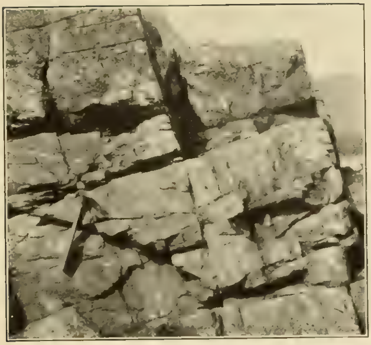
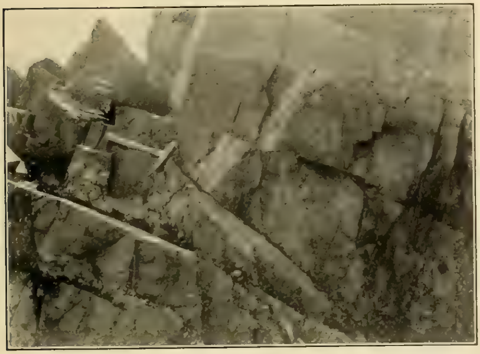
[1] Petrographic microscopic descriptions by H. E. Merwin.



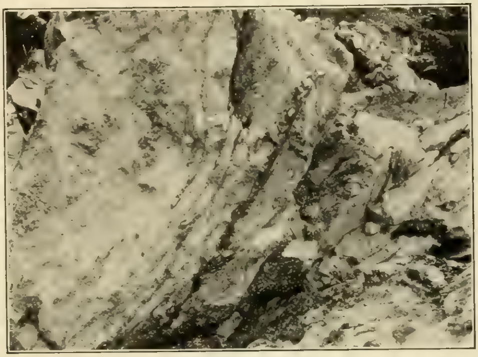
A. DIORITE ON SOUTH SIDE OF LYMAN ANCHORAGE NEAR CONTACT WITH KASAAN FORMATION.

The diorite shows parallel arrangement of the feldspar, indicating flow structure.



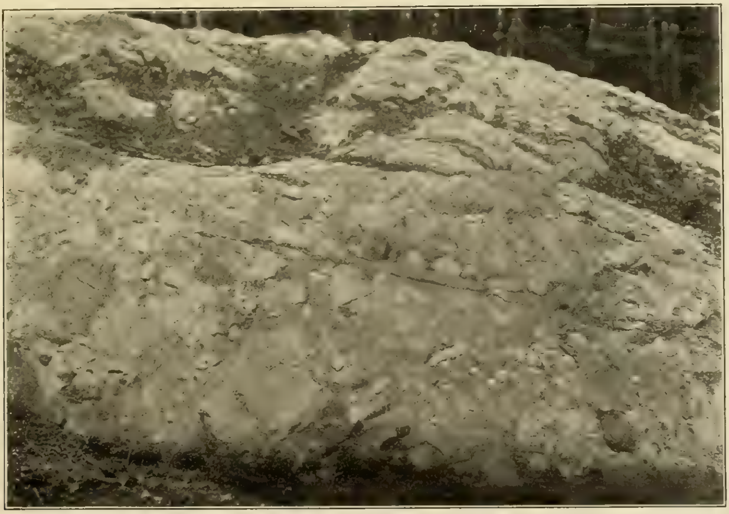
B. DIORITE ONE-HALF MILE SOUTH OF LYMAN ANCHORAGE.

An aplite dike (of lighter shade in view) cuts the diorite and is faulted along a joint plane.



C. LIMESTONE ON SHORE 1 MILE SOUTHEAST OF LYMAN ANCHORAGE.

The beds of limestone are in places metamorphosed and traversed by small dikes of basalt.



D. ALTERED CONGLOMERATE SHOWING PORPHYRY PEBBLES IN A GROUNDMASS OF GRAYWACKE.

View taken at Rush & Brown mine.

diorite a foot or more in diameter. These phenomena near the contact of the largest intrusive mass on Kasaan Peninsula seem to show that there was a lack of uniformity in the composition of the original magma at the time of its intrusion and that after the first intrusion and consolidation fracturing occurred and additional magma was forced into the fractures. A further consolidation, accompanied by fracturing and by the introduction of magmatic solutions, may account for the pegmatitic and aplite and alaskite dikes which are most common in the granitic rocks near the contact. (Pl. XVI, *A*, *B*.)

At Lyman Anchorage the granitic intrusive at the contact is gneissoid, the structure striking N. 20° E. and the dip being vertical, parallel to the contact. This dioritic rock is cut by veins and dikes, the largest 100 feet wide, of orthoclase quartz pegmatites or alaskites, and some of the veins grade into quartz veinlets a few inches thick. Most of the minerals in these dikes and veins are coarsely crystalline. At the contact the intruded rocks have been altered to an amphibole schist, so that the line between the intrusive and intruded rock is not always clearly defined. A short distance away from the contact the intrusive rock is diorite of uniform texture, though it contains inclusions of basic diorite and amphibolite. These inclusions as well as the diorite some distance from the contact are cut by the pegmatitic dikes.

The main diorite mass on Tolstoi Mountain, at the north end of Kasaan Peninsula, is almost identical in composition and character with that at Grindall Point, and around its contact similar phenomena were observed. A typical specimen (No. 199) from Tolstoi Mountain has already been described (p. 75).

The gabbro is limited to the mass that includes the Goodro mine and extends northwestward beyond the Rush & Brown mine, but only part of this mass is actually gabbro. The western part of this intrusive mass, which is indicated on the map (Pl. XV), is made up of normal diorite. The eastern part of the mass is a coarsely crystalline augite gabbro (see descriptions of specimens 411 and 254, p. 75), sufficiently rich in magnetite to deflect the compass. At the Goodro mine the gabbro is cut by dikes of diorite and pegmatite, so the gabbro is somewhat older than the diorite. Both the gabbro and diorite are altered in places and contain epidote and calcite. At this mine a great number of dikes and veins of feldspar and quartz, many of them containing coarse crystals of amphibole, lie near the ore body.

Near the Rush & Brown mine the diorite contains numerous inclusions of the gabbro, which is therefore the older. Here also the gabbro and diorite are cut by dikes and veins of pegmatite and have been somewhat altered by the mineralizing solutions that deposited the epidote, calcite, and pyrite.

Granitic intrusive of the syenite type was found near the contact of the large intrusive mass at Boggs Landing. Granitic intrusive having a porphyritic texture occurs in large dikes and is described under the heading "Porphyritic intrusives" (below). At many places syenite forms a part of the granitic intrusive masses near their contacts and is merely a phase of the general dioritic mass. The syenite, however, contains inclusions of diorite and fills fractures in the diorite and is therefore regarded as of somewhat later intrusion that the diorite, though in all other features the two types of rock are identical.

The granites, which are also regarded as a phase of the dioritic intrusives, are similar in occurrence to the syenites. At a point 4 miles southeast of Hadley there is a mass of granite nearly half a mile wide, and at a point a mile northwest of Hadley, at the contact of a large mass of diorite, there is a similar granitic mass. A third and larger mass of granite lies north of Karta Bay. The rock of this mass, however, is rich in plagioclase and approaches a quartz diorite in composition. The features of the occurrence of these granitic masses are the same as those of the diorite.

PORPHYRITIC INTRUSIVES.

GENERAL CHARACTER AND DISTRIBUTION.

In general the porphyritic rocks occur in the form of dikes that are from 10 to 100 feet wide and stand nearly vertical. Most of these dikes strike north to northwest but some strike nearly east. In color the porphyries are greenish to pinkish and generally show well-developed though closely crowded feldspar crystals. The phenocrysts are principally plagioclase feldspar and augite or hornblende, the groundmass being microgranular and made up essentially of feldspar and some quartz. The porphyries are generally of syenite, those of granite diorite being scarcer. Ore deposits occur at the contacts of some of the larger porphyry dikes, and although most of them are commercially unimportant they are of geologic interest and are described under the heading "Copper ores" (p. 85). The distribution of the porphyries is shown on the geologic map (Pl. XV).

DIORITE PORPHYRIES.

It was not generally possible in the field to distinguish the diorite porphyries from the related syenite porphyries. In fact, the diorite porphyries form a transitional group between the diorite, the syenite porphyries, and the granite porphyries.

In these porphyries quartz, orthoclase, and augite are more abundant than in the diorite, and the plagioclase is more sodic. Some of the diorite porphyry dikes are more basic near the contact. A dike 60 feet wide, on the east side of Tolstoi Bay, contains in its central part about 40 per cent of hornblende, which is mostly in phenocrysts associated with plagioclase but is partly in the groundmass with about equal amounts of quartz, orthoclase, and plagioclase (specimen 222). A specimen taken near the contact (specimen 223) contains about 65 per cent of hornblende, mostly in the fine-grained groundmass.

But few of the specimens of diorite porphyry examined were fresh enough to warrant more definite statements concerning their original mineral composition than have already been made. The two specimens described below, taken from places near the coast about one-fourth of a mile west of Hadley, are comparatively fresh.

Specimen 46. Augite diorite porphyry. The hand specimen is a dark-gray medium-grained porphyritic rock with abundant phenocrysts of plagioclase and augite, the augite presenting many glistening cleavage surfaces and crystal faces.

In the thin section the plagioclase is seen to be twinned according to both the Carlsbad and albite laws, and its composition was determined as about Ab_1An_2. The augite phenocrysts are in part glassy, clear, and faintly colored, and are in part uralitized. Some augite crystals are surrounded by primary hornblende. The groundmass consists of plagioclase, augite, hornblende, biotite, orthoclase, and quartz. Orthoclase is intergrown with quartz. Apatite and magnetite are abundant, the apatite forming numerous trellis-like structures composed of long, slender needles, structures so frail that it is difficult to understand how they could have been preserved while the rock was in process of solidification. The plagioclase forms about 50 per cent of the rock, and the dark constituents 35 per cent.

Specimen 48. Diorite granophyre. This is a dark reddish-gray rock, fine grained and porphyritic. The phenocrysts are strongly zoned plagioclase, ranging in composition from basic andesine through oligoclase, the interiors being most calcic. The groundmass consists essentially of plagioclase, quartz, and orthoclase, the last two minerals being intergrown as micropegmatite. Quartz and orthoclase occupy about 25 per cent of the area of the slide; dark silicates, hornblende, and biotite, less than 10 per cent. Magnetite, titanite, and apatite are accessories.

SYENITE PORPHYRIES.

Most of the syenitic rocks are of porphyritic texture, but some are granitic. They occur in dikes and contain the highly alkalic differentiation products of the diorite magma. These alkali rocks form a series that stands between two extreme types, one highly potassic, the other highly sodic. The mass of the sodic type is much the greater, judging from the relative abundance of the specimens of the two types collected. Soda should preponderate in the syenites on account of the relatively high soda content of the diorite from which they were derived.

Specimen 259. Calcite syenite porphyry, from a dike near the head of Karta Bay.

In the hand specimen the rock is light yellowish gray, fine grained, and porphyritic. Equidimensional phenocrysts of faintly greenish feldspar about 3 millimeters in diameter form about 2 per cent of the rock; other phenocrysts of rhombic habit, about 0.5 millimeter in diameter, make up a larger percentage. On weathered parts of the rock the phenocrysts have been dissolved and the cavities filled with limonite. The phenocrysts effervesce freely in hot dilute hydrochloric acid, and therefore appear to be ferruginous calcite. Weathered surfaces of the rock are chocolate-colored, and broken surfaces of weathered parts are light brown specked with dark brown.

In the thin section the rock is seen to be holocrystalline. The phenocrysts of feldspar have symmetric extinction angles of albite twins as high as 16°, and refractive indices of about $\alpha = 1.529$, $\gamma = 1.537$. These angles and refractive indices point to albite. The borders of the phenocrysts show the effects of resorption and subsequent renewed growth. The latest material appears to have been crystallized contemporaneously with the groundmass, as shown by interpenetration. The calcite phenocrysts occur as euhedral crystals, having the habit of the unit rhombohedron. By a geometric analysis of three slides these crystals were found to make up 3 to 6 per cent of the rock mass. Small calcite rhombs are included in the albite phenocrysts, showing that the calcite was the earliest of the essential constituents to crystallize. The refractive index ω of the calcite is 1.742 ± 0.003. For pure calcite $\omega = 1.658+$. The high refractive index of the phenocrysts must be due to the presence of siderite.

The groundmass consists of sheaf-like aggregates of finely fibrous feldspar. A few of the coarser fibers, possibly phenocrysts, exhibit albite twinning and an observed maximum symmetric extinction of 17°. The refractive indices α and γ are 1.524 and 1.531. From these facts alone it would be difficult to decide whether the feldspar should be considered as soda orthoclase or as a potash-rich albite. Too little is known of the relation between chemical composition and the refractive index of the soda-potash feldspar to make one the basis for estimating the other. No feldspar of lower refractive index was found in the slides. Interstitial quartz occurs in small isolated patches and probably as thin films among the feldspars. Its bulk is estimated at 5 per cent or less. From 2½ to 3 per cent of calcite is scattered through the groundmass in minute rhombs, either singly or clustered. The accessory minerals, each amounting to less than 1 per cent, are muscovite, apatite, possibly zircon, and a fibrous mineral having the general optic properties of a yellow-green amphibole.

An analysis of this rock by R. C. Wells has been calculated into normative minerals according to the methods of the quantitative system, except that, the lime being insufficient to combine with the CO_2 to form calcite, FeO was used to form siderite. In classifying the rock siderite was grouped with calcite.

The ratio of calcite to siderite calculated from the analysis is lower than would be inferred from the refractive index of the calcite phenocrysts. It is possible that the small rhombs of calcite in the groundmass are richer in iron than the phenocrysts.

Chemically and texturally the rock is a distinctly new type. Chemically, however, it can be made to conform to the quantitative system of classification by changing the method of calculating the minerals as described above. Texturally, the occurrence of calcite in euhedral crystals in an igneous rock is unique. There can scarcely be any doubt that the calcite crystallized directly from the magma. According to Adams and Barlow,[1] primary calcite has been found in granular form in igneous rock. The rocks described by them do not contain free silica, as this rock does.

Analysis of calcite syenite porphyry.

[By R. C. Wells.]

SiO_2	63.41	ZrO_2	0.04
Al_2O_3	16.86	CO_2	2.93
Fe_2O_3	None.	P_2O_5	.12
FeO	2.88	SO_3	None.
MgO	Trace.	Cl	None.
CaO	1.47	S	.05
Na_2O	7.38	MnO	.28
K_2O	3.09	BaO	None.
H_2O-	.29		
H_2O+	.42		99.48
TiO_2	.26		

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[1] Adams, F. D., and Barlow, A. E., Geology of the Haliburton and Bancroft areas, Ontario: Geol. Survey Canada, Mem. 6.

Calculated mineral composition.

Corundum	1.06	Apatite	0.34
Quartz	8.74	Rutile	.26
Orthoclase	18.35	Water	.71
Albite	62.35		
Calcite	2.30		99.21
Siderite	5.10		

This calculated composition corresponds to nordmarkose.

Specimen 291. Augite trachyte, from a point near the head of Karta Bay. This is a greenish-gray medium-grained porphyritic rock containing abundant tabular phenocrysts of orthoclase arranged in flow structure. Augite forms phenocrysts and is a chief constituent of the groundmass. Magnetite is easily recognized by means of a lens.

Under the microscope the orthoclase phenocrysts appear to make up about 50 per cent of the mass of the rock. They are fresh and almost glassy, much resorbed, and hold inclusions of augite, plagioclase, and magnetite. One slender crystal is bent in an arc of 9°. The bending has not caused perceptible fracture, but the positions of extinction instead of being turned 9° are turned 13° on the convex side and 6° on the concave side of the crystal. From determinations of the refractive indices of the orthoclase (made by methods based on immersion) it appears to be a nearly pure potash feldspar ($\alpha = 1.517 \pm 0.001$, $\gamma = 1.525 \pm 0.001$). The extinction on 010 is 7° and the optic axial angle near the maximum for orthoclase. Augite in crystals of various sizes makes up about 30 per cent of the mass of the rock. Biotite that is altered to chlorite and some epidote, a very minor constituent, were formed later than the augite and orthoclase. The groundmass consists of almost completely altered plagioclase, the crystals having been originally not much smaller than those of the phenocrysts. Muscovite and epidote are the chief present constituents of the groundmass. The freshness of the orthoclase and augite and the very far advanced alteration of the plagioclase and biotite are remarkable. All the observed extinction angles of the plagioclase were less than 13°, so that it is nearly pure albite.

Syenite lamprophyre dikes, consisting largely of ferromagnesian minerals with subordinate alkali feldspars, were intruded at the same general period as the syenites. Such dike rocks bear the same relation to the syenites that the gabbros bear to the diorite, with the exception that the gabbros consolidated as marginal facies of the diorite, where they had accumulated during differentiation. While the gabbros were in process of consolidation the forces that caused fissuring were not strongly active, but while the lamprophyres were consolidating these forces must have been nearly at their period of greatest activity. Specimen 108, from a dike cutting albite syenite, contains about 40 per cent of augite in phenocrysts, 15 per cent of hornblende, 10 to 15 per cent of chlorite, a little calcite, and 30 per cent of albite. Specimen 250 contains about 70 per cent of ferromagnesian minerals (now chiefly uralite and epidote) and 30 per cent of orthoclase.

GRANITE PORPHYRIES.

35. Quartz porphyry, from a dike about 2 miles northwest of Hadley. This rock is nearly white and translucent, containing scattered phenocrysts of quartz in a very fine grained groundmass of plagioclase, quartz, and muscovite. The phenocrysts have been considerably resorbed.

769. Granophyre, a dark-red fine-grained rock from a dike in Stevenstown tunnel. A first generation of albite in scattered crystals was followed by a second generation of albite in abundant idiomorphic crystals. The groundmass is micropegmatitic, quartz being intergrown with both orthoclase and plagioclase. Muscovite, biotite, and hornblende are accessories. Primary calcite appears in this rock in two forms, first, as an early crystallization in distinct rhombs included in the albite; second, in interstitial intergrowth with quartz as a final crystallization.

AGE OF THE PORPHYRIES.

The porphyries are presumably younger than the granitic intrusives because of their relation to these intrusives in composition and occurrence. The syenite porphyries at least are older than the ore deposits, for many of the contact ore bodies lie at their contact. Such ore deposits were not noted at the contact of the diorite porphyry dikes, which crosscut the syenite porphyries and hence are younger than the syenites.

PEGMATITES, ALASKITES, AND APLITES.

GENERAL FEATURES.

Dike or vein rocks that are made up essentially of feldspar and quartz—such as the pegmatites, aplites, and alaskites—are not plentiful on Kasaan Peninsula and are found only at places near the periphery of the large granitic intrusive masses. At these places such dikes cut both the large intrusive masses and the intruded sedimentary rocks. They occupy narrow seams and large fissures and strike in various directions, following no particular systems of fracturing. In mineral composition these rocks consist essentially of orthoclase, some albite, and quartz. The coarsely crystalline types are known as alaskites and pegmatites, whereas the fine-grained rocks of practically the same composition are called aplites. Only two specimens of these rocks, representing a somewhat peculiar type, are described here.

PETROGRAPHIC DETAIL.

Specimen 137. Calcite alaskite aplite, a fine-grained light-pink rock, when examined microscopically, was found to consist of about 60 per cent of orthoclase, 30 per cent of quartz, 9 per cent of primary calcite, and a little plagioclase. The red color of the rock is due to dusty hematite sprinkled through the feldspar. The rock is very fresh. (See Pl. XVII, *C*, *D*.)

Two periods of crystallization can be made out. In the first period quartz, orthoclase, and a little calcite formed an even-grained mass penetrated by spider-like stringers of the mother liquor. In the second, the mother liquor solidified in a partly granular, partly poikilitic mass. Orthoclase and calcite are much more abundant in the later crystallization, and the calcite is coarser grained and anhedral.

The proportion of orthoclase to plagioclase is much greater in this rock than in any other examined.

Specimen 767. Alaskite aplite. This rock, taken from a dike 1 inch wide in the Stevenstown tunnel, contains 10 to 15 per cent of albite, 40 to 50 per cent of orthoclase and microcline, and 30 to 35 per cent of quartz. The dike cuts syenite. From the broken phenocrysts in the syenite parallel growth of feldspar has taken place in the dike, indicating that the temperature of the dike was not very different from the temperature of the syenite when the dike was intruded. The feldspar of the syenite is considerably altered by weathering, but that of the dike is still fresh. It is this difference in alteration that makes it possible to trace the boundary of the dike through optically continuous crystals.

AGE.

Their composition and their mode of occurrence as fillings of small and wide cracks having various courses, in both the intrusive and intruded rocks, suggest, as has often been pointed out by geologists, that the magma which formed these dike rocks was injected soon after the intrusion of the diorites and that the fissures they fill are contraction cracks caused by the shrinkage that accompanied the cooling and crystallization of the igneous intrusive masses.

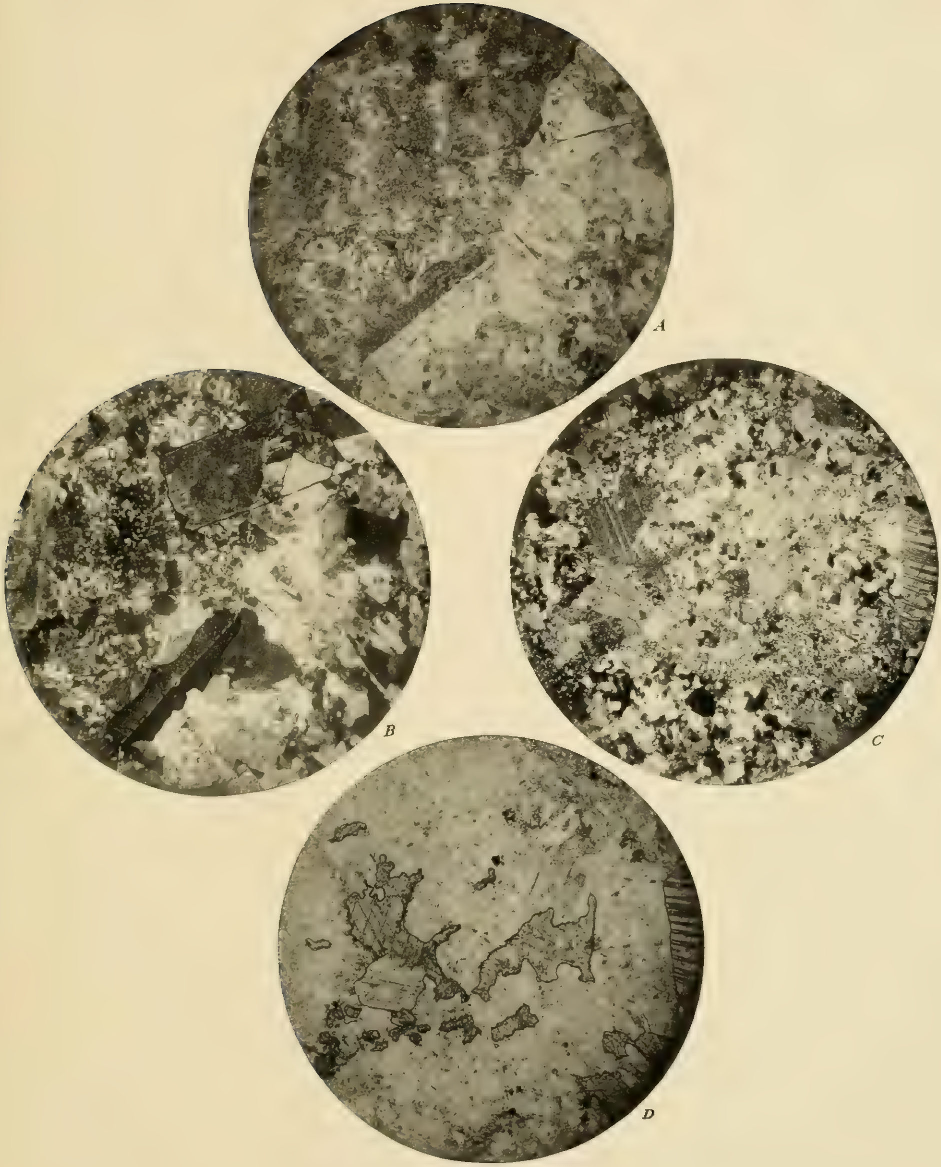
The rocks of this group are assumed to have been derived from the same magma that furnished the granitic intrusives and to have been formed from aqueo-igneous solutions that contained more water than the diorite magma.

The age of the pegmatite and aplite as compared with that of the porphyries is not shown by intersection, but the intimate relations of the granitic intrusives to the pegmatite and aplite when compared with the relations of these intrusives to the porphyries show that the porphyries are younger than either the granitic intrusives or the pegmatites and aplites.

PLATE XVII.

A, B. Microscopic views of alaskite aplite (specimen 767, see p. 81). *A*, Section showing contact of an alaskite aplite dike (lighter area) with syenite. *B*, Same section under crossed nicols, showing optical continuity between the crystals of microcline (*a*) and of orthoclase (*b*) in the syenite and the aplite. Dotted line indicates line of contact.

C, D. Microscopic views of calcite alaskite aplite (specimen 137, see p. 81). *C*, View under crossed nicols, showing texture. Early crystallization is indicated by the coarse granular texture and later crystallization by the areas of calcite (outlined) and the fine-grained texture. *D*, Same section without nicols crossed, showing areas of calcite.



THIN SECTIONS OF ALASKITE-APLITE AND CALCITE-ALASKITE FROM KASAAN PENINSULA.

CONTACT ROCK.

GENERAL FEATURES.

The name "contact rock" is applied to the metamorphic rock that occurs in zones around the granitic intrusive masses and that has at many localities replaced the granitic rock. In composition it consists mainly of garnet, diopside, and feldspar, but it contains also hornblende and tremolite and some calcite. It includes masses and disseminated particles of sulphide minerals and masses of magnetite containing sulphide ores. A sample of this rock (specimen M1) taken for chemical analysis is described below.

PETROGRAPHIC DETAIL.

Specimen M1. Rock from contact zone between the limestone and the intrusive rock at the Mamie mine, 1¼ miles south of Hadley.

The chemical analysis, made by George Steiger, shows that this rock has the composition of a monzonite rich in lime. The intrusive rock at the Mamie mine goes under the field name of syenite, but an examination of six thin sections from several drill cores of the partly altered intrusive rock shows that considerably less than half the feldspar is orthoclase and that the plagioclase is basic oligoclase and acidic andesine. The rock contains also a small amount of quartz. The ferromagnesian minerals are much subordinate to the feldspar. The mineral composition therefore shows that the rock is a monzonite, and that it is part of the intrusive mass. Its slightly higher content of lime than most monzonites is probably due to lime brought in from the adjacent limestone.

The rock consists of about 50 to 60 per cent of plagioclase (albite and oligoclase), 10 per cent of orthoclase, 20 per cent of epidote, and 10 to 15 per cent of calcite. It contains also a lath-shaped mineral, confined chiefly to secondary veinlets, which is somewhat unlike ordinary rock-making minerals. Its index of refraction ranges from 1.58 to 1.625, its optic axial angle is large, optical character positive, birefringence rather strong, extinction parallel or nearly so, and elongation positive. These characters agree very well with pectolite or prehnite.

In the hand specimen the rock is greenish gray in color and aphanitic.

Analyses of monzonites from Kasaan Peninsula, Alaska (A), and from Babcock Peak, Colo. (B).

[Analysis A by George Steiger; B by H. N. Stokes.]

	A	B		A	B
SiO_2	58.87	57.42	TiO_2	0.59	0.86
Al_2O_3	17.12	18.48	CO_2	.84	None.
Fe_2O_3	1.96	3.71	P_2O_5	.20	.26
FeO	.95	2.10	Cl		.03
MgO	1.75	1.71	S	.09	None.
CaO	8.00	6.84	MnO	.10	.09
Na_2O	4.64	4.52	BaO	.06	.15
K_2O	4.34	3.71	SrO	.02	.08
H_2O-	.13	.28	Li_2O		Trace
H_2O+	.81	.08			

DIABASES AND BASALTS.

GENERAL CHARACTER.

The more basic intrusive rocks, as well as the most recent, are essentially diabase and basalt. These rocks form dikes that range in width from 1 foot to many feet, in texture from microgranular to coarse granular, and in color from dark green to black. The dikes cut the country rock at many places and penetrate the joints in the granitic intrusives. They also cut the ore deposits in most of the mine workings. The diabase dikes are generally larger, more coarsely crystalline, and older than the basalt dikes, which are cut by the diabase dikes.

PETROGRAPHIC DETAIL.

Specimen 265. Hornblende dolerite. This rock, from the north shore of Karta Bay, contains about 45 per cent of labradorite in phenocrysts surrounded by a groundmass including both granular and poikilitic hornblende. The hornblende is of the typical basaltic variety, having a maximum extinction of 10° and pleochroic as follows: Z and Y dark red-brown, X very light yellow-brown, absorption $Z > Y > X$. This hornblende is rare in the basic igneous rocks of southeastern Alaska, its place usually being taken by varieties of common hornblende. The rock contains about 10 per cent of magnetite, which crystallized early, in branching and simple octahedral forms., The rock contains a small amount of biotite, which is pleochroic, ranging from almost black to very light yellowish brown.

Specimen 65. Dolerite (diabase), from a dike about 4 miles south of Hadley. A medium to fine grained rock containing zoned plagioclase of composition ranging from Ab_2An_3 to Ab_1An_3. Titaniferous augite occurs both in grains and in irregular masses having an ophitic intergrowth of feldspar. Magnetite inclosing feldspar forms large poikilitic masses.

Specimen 11. Hornblende basalt, from a dike 3½ miles northwest of Hadley. This rock is hypocrystalline porphyritic, having phenocrysts of hornblende, completely altered to serpentine and chlorite, scattered through a groundmass of plagioclase, augite, basaltic hornblende, iron ore, and glass. The augite is in part at least earlier than the feldspar, the basaltic hornblende is in part earlier and in part later than the feldspar. Interstices among the minerals once probably filled with glass are now masses of calcite and chlorite. Many small amygdules have been lined with chlorite and subsequently filled with calcite.

Specimen 386a. Melaphyre (basalt). A fine-grained hypocrystalline rock containing scattered phenocrysts of serpentinized augite and feldspar (Ab_2An_3). The partly glassy groundmass or base is filled with dark-brown needle-shaped crystallites, which extinguish obliquely. Amygdular cavities are filled with calcite.

AGE.

The geologic period in which these basic diabase and basaltic dike rocks were intruded into the metamorphic rocks of Kasaan Peninsula can be determined only by their relations to the other intrusive rocks. These dike rocks intersect the granitic intrusives, the porphyries, and the ore deposits, and also occur along joint planes both in the intrusive and intruded rocks. They are therefore the most recent rocks formed on Kasaan Peninsula and, judging from the occurrence of these rocks at other localities in the Ketchikan district, they are probably of Tertiary age. The basalt dikes crosscut the dikes of diabase and dolerite and are therefore the younger.

GEOLOGIC HISTORY.

The geologic record of events on Kasaan Peninsula begins with the deposition of a series of fragmental rocks, now represented by banded quartzites, graywackes, and conglomerates, and some tuffaceous beds. This series includes narrow beds of limestone which, though no fossils were found in them, are believed to be Devonian. The entire series is much folded and its beds stand nearly vertical, so that its thickness is difficult to determine, but it is believed to be several thousand feet thick.

There is no other geologic record until the early part of the Mesozoic era, but in the meantime these sediments were subjected to intense metamorphism and partial recrystallization due to pressure of overlying strata and to structural changes, which caused the beds to become intricately folded, the direction of the axes of folding being generally northwest.

During early Mesozoic time the rocks of the region were invaded by granitic intrusives. This granitic intrusion was a most important geologic event, as it caused the deposition of the ore bodies. It extended over a long period and produced much fracturing, folding, and metamorphism of the invaded rocks. This intrusion was probably deep seated and the intruded rock solidified far below the surface of that time, as there is no evidence that it extended to the surface. After the granite solidified the pegmatite-aplite dikes were injected from the still fluid portions of the granitic magma. Cracks and fissures were then formed near the contact of the intrusive rocks. These openings, which may have been caused by contractions due to further cooling of the intrusive mass, served as channels for carrying the mineralizing solutions from which the ores were deposited.

The porphyritic dike rocks were also intruded into the sedimentary strata about this time and produced much metamorphism in the adjacent sediments, and locally along the contact rock sulphides were formed, though so far as known less abundantly than along the granitic masses.

A period of active erosion followed the uplift of the Kasaan Peninsula caused by the invading granitic masses, and during this epoch the main valleys, Clarence Straits and Kasaan Bay, which may have been begun at an earlier period, were greatly deepened. This period of erosion continued until the underlying granitic intrusives were exposed and the main features of the present topographic relief were formed. Later the land subsided, these main valleys became salt water channels, and then followed the ice period, which submerged these mountains under a sea of ice. The ice streams advanced from the northwest, carried erosion still farther, and brought with them bowlders and débris foreign to the region, depositing this material on the hilltops and forming bench deposits on the valley slopes. After the retreat of this ice sheet erosion continued to deepen the gulches and remove the deposits left by the glaciers.

The effects of this erosion on the ore deposits, located as they are on the mountain tops and hillsides in rocks little affected by chemical action, such as oxidation, has been extensive and therefore the ore deposits are primary, whereas those in most mineral-bearing regions are secondary.

COPPER ORES.

GENERAL FEATURES.

The copper deposits on Kasaan Peninsula consist of primary ores which show but slight traces of weathering or of concentration by circulating waters. They are similar in occurrence to the ores on Copper Mountain, which have already been described (p. 44).

Four types or ore deposits, defined principally by their mineral composition but also by their mode of occurrence, have been recognized:

1. Contact deposits forming irregular masses along intrusive contacts and consisting of chalcopyrite-magnetite ores and chalcopyrite-pyrrhotite ores associated with amphibole, garnet, feldspar, epidote, and calcite.
2. Disseminated deposits forming irregular, ill-defined masses in gabbro intrusives, and consisting of bornite-chalcopyrite ores intimately associated with the primary minerals of the intrusive rock and secondary epidote and calcite.
3. Shear-zone deposits occupying fissures along shearing planes in the graywackes, consisting of chalcopyrite-pyrite-sphalerite ores associated with a quartz-calcite-barite gangue.
4. Vein deposits occupying fissures in limestones and granitic intrusives and consisting of galena-sphalerite-chalcopyrite ores in a quartz-calcite-barite gangue and auriferous pyrite in quartz veins.

The deposits of the first and third types are the principal copper producers (1908). Deposits of the second type are being developed at several places, and from one mine—the Goodro—shipments of ore taken from deposits of this type have been made. Deposits of the third type have been developed at the Rush & Brown mine and at certain prospects. The vein deposits of the fourth type have been prospected at several points but have not yet been mined.

CONTACT DEPOSITS.

OCCURRENCE.

The term "contact deposit" is here restricted to mineral veins or ore masses that have been formed by contact-metamorphic action and that carry the minerals characteristic of such action. A contact deposit must therefore lie near an intrusive rock, though not necessarily at its contact.

At the time of their intrusion the igneous rock masses or dikes forced their way through the sedimentary rocks, to some extent folding and fracturing them. While they were cooling both the intruded and intrusive rocks naturally shrunk somewhat, and the shrinkage caused cracks and fissures to form near the contacts. These fissures became channels for mineral-bearing solutions, derived, presumably, from great depths, where the temperature was high. On ascending along the contacts, where the temperature was lower, these solutions deposited their mineral content and to some extent replaced the rocks along their course. The contact deposits therefore lie within the contact zone, between the intrusive and intruded rocks, and are believed to have been derived from the same magma that formed the adjacent igneous rocks. Their genesis, however, will be discussed elsewhere (p. 102).

CHARACTER.

The minerals commonly associated with the contact deposits are chalcopyrite, pyrrhotite, pyrite, and magnetite. The gangue minerals are principally garnet and pyroxene, with which are associated variable quantities of epidote, calcite, quartz, amphibole, wollastonite, and feldspar, besides several rarer minerals. These minerals are typical of contact-metamorphic deposits. Mineralogically, these ores differ from the ores of other deposits, especially in the contemporaneous formation of metallic oxides and sulphides, principally of iron, in association with the various lime-silicate minerals named above.

The ore deposits themselves within the contact zone consist of irregular masses ranging in diameter from a few feet to 100 feet or more. Few of them have well-defined limits, most of them merging gradually into barren contact rock. At a few places the ore-bearing contact rock is surrounded by the granitic intrusives; at other places it is surrounded by sedimentary rocks, no surface exposures of the intrusive rock appearing near it. Veins of contact rock carrying ore also cut the intrusive as well as the intruded rocks, though these veins are of little commercial importance.

The copper ore is entirely chalcopyrite and occurs in small masses and grains scattered through the contact rock, and also in the masses of magnetite. Only the parts of the contact rock or magnetite bodies that are sufficiently rich in copper to be profitably mined are regarded as ore.

EFFECT OF INCLOSING ROCK ON ORE FORMATION.

The size of the contact deposits and the width of contact rock at any particular place depend to some extent on the size of the intrusive mass at that place. The largest contact deposits on Kasaan Peninsula are those that have been exploited at the Mamie and Mount Andrew mines, which are near the large intrusive mass that constitutes the southeastern half of the peninsula. Smaller deposits, some of them, however, richer in copper, lie near smaller intrusive masses. These smaller deposits are exploited by the It and the Rush & Brown mines. Still smaller deposits lie near dikes of syenite porphyry and many of them have been prospected, though none have yet afforded ore bodies large enough to be mined profitably.

The general occurrence of the contact deposits at places where limestone is the intruded rock suggests that the lime carbonate helped to effect the precipitation or development of the ores at such points.

DISSEMINATED DEPOSITS.

Irregular disseminated bodies of copper ore occur in an intrusive belt of gabbro that extends along the northeast side of the salt chuck at the head of Kasaan Bay, extending northwestward and averaging about a mile in width. Copper ore has been found at only a few places in this intrusive belt and has been mined only at the Goodro mine.

Where the ore deposits occur the gabbro is partly recrystallized and contains large crystals of biotite and crystals of feldspar having a poikilitic mottling due to partial replacement by biotite. The rock also contains epidote and groups of large crystals of orthoclase, with biotite and epidote and some garnet. The bornite and chalcopyrite ores occur with the secondary minerals last named. It appears that these ore minerals were introduced into the gabbro by the same mineralizing agencies that caused the metasomatic development of the secondary minerals. These agencies may have been directly related to those that produced the contact deposits; and if so, these deposits are only a phase of the contact deposits.

SHEAR-ZONE DEPOSITS.

Ore bodies representing shear-zone deposits occur near the head of Karta Bay, at the Rush & Brown mine and at the Venus prospect. These deposits consist of lenticular veins, from a few inches to a foot or more wide, of massive sulphide minerals, the veins being distributed along shear zones, from 2 to 10 feet wide, in the graywacke country rock.

The deposits contain chalcopyrite, pyrite, and some sphalerite in a gangue of much-altered graywacke and some quartz and calcite.

VEIN DEPOSITS.

Vein deposits that occupy fissures in limestone, from 1 foot to 5 feet wide, have been prospected on Kasaan Mountain. They contain galena, tetrahedrite, some sphalerite, and chalcopyrite, their principal valuable metallic content being lead and silver and some gold. The gangue minerals are quartz, calcite, and barite, but chiefly quartz.

Quartz veins carrying pyrite and some gold and chalcopyrite have been prospected on Grindall Point, at the south end of Kasaan Peninsula. The veins occur in the granite intrusives and measure 6 feet or more in width. These deposits have been exploited by prospect shafts and tunnels, but the ore is of low grade and no great amount of it has been found.

PERSISTENCE OF ORE BODIES.

These various types of ore bodies show different degrees of persistence. The contact deposits are generally small, irregular masses and are no more persistent in depth than they are laterally, but where these masses have been found in a wide contact zone further exploration will probably reveal similar ore masses, both laterally and in depth. The copper-iron sulphide deposits in shear zones in the stratified rocks are more persistent than the contact ore bodies and probably go deeper. The vein deposits in the limestones will also be extensive in depth, but will vary greatly in width, in places narrowing to a mere seam. To judge from like deposits elsewhere, possibly the lead-silver ores will be replaced by copper ores in depth.

MINERALS OF THE DEPOSITS.

The minerals in the ore deposits on Kasaan Peninsula are very similar to those that occur in the Copper Mountain region already described (p. 47). It is not necessary to repeat these descriptions here, but a list of the minerals found in the different types of ore deposits is given below.

Contact deposits.		Disseminated deposits.	Shear-zone deposits.	Vein deposits.
Chalcopyrite.	Garnet.	Chalcopyrite.	Chalcopyrite.	Galena.
Pyrite.	Epidote.	Bornite.	Pyrite.	Tetrahedrite.
Pyrrhotite.	Hornblende.	Chalcocite.	Sphalerite.	Chalcopyrite.
Magnetite.	Diopside.	Pyrite.	Galena.	Sphalerite.
Specularite.	Scapolite.	Native copper.	Quartz.	Pyrite.
Ilvaite.	Wollastonite.	Epidote.	Sericite.	Quartz.
Molybdenite.	Orthoclase.	Amphibole.	Calcite.	Calcite.
Azurite.	Chlorite.	Biotite.	Chlorite.	Siderite.
Limonite.	Quartz.	Calcite.	Amphibole.	Barite.
Malachite.	Calcite.	Quartz.		Chlorite.

In the contact deposits on Kasaan Peninsula the amount of hornblende and feldspar in the contact rock is greater than in the similar deposits on Copper Mountain, for the graywacke, which at most places forms the hanging wall of these deposits, has entered largely into their composition. Tremolite and wollastonite are rare, having been found only where limestone beds occur at the contacts. No zeolite was found. A few specimens of ilvaite with calcite matrix were noted in the contact deposits. (See Pl. XIX.)

Bornite and chalcocite, which occur in the disseminated deposits, were not found in the Copper Mountain area. The mode of occurrence of the minerals in the vein and shear-zone deposits is similar in both districts.

MINING ON KASAAN PENINSULA.

HISTORY.

Copper was first discovered on Kasaan Peninsula by the Russians about 1865. Between 1895 and 1900 most of the mineral locations were made and the mine developments were begun. During the following five years there were more extensive developments and nine plants were installed, aerial tramways were erected, and a smelting plant was built at Hadley. Copper was first produced from these mines in 1905, the year in which the Hadley smelter was completed. Copper production continued, gradually increasing in amount, until the autumn of 1907, when most of the mines ceased operations.

In the summer of 1908 the Hadley smelter was again in use, and some of the mines renewed operations, but for a short period only. From 1909 to 1913 the smelter was idle, though certain of the mines continued operations, shipping the ore to the Tyee and Tacoma smelters.

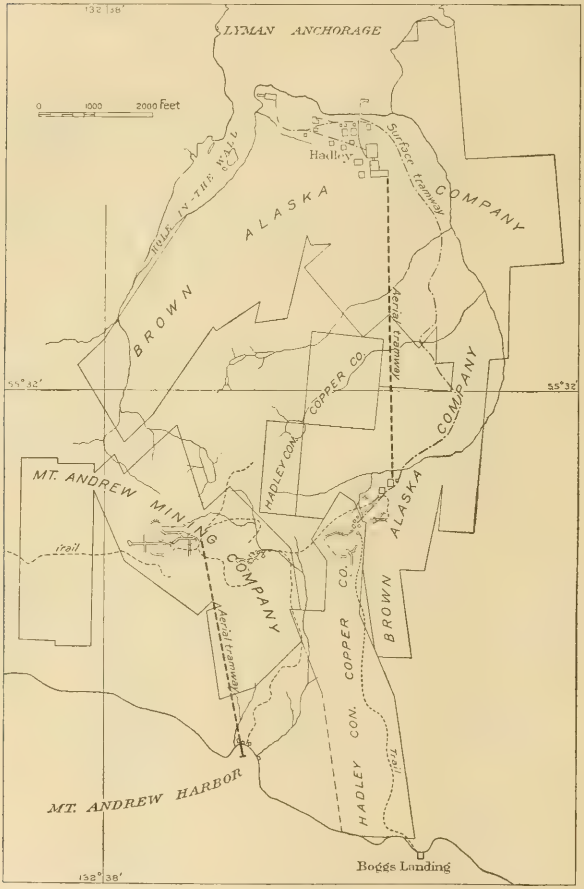


FIGURE 7.—Map showing properties of the Brown Alaska Co., Hadley Consolidated Copper Co., and Mount Andrew Mining Co. (1908).

MINES SOUTH OF HADLEY.

GENERAL FEATURES.

Three of the principal mines on Kasaan Peninsula are near the summit of the mountain ridge about 1½ miles south of Hadley, at altitudes of 700 to 1,400 feet. These are the Mamie, Stevenstown, and Mount Andrew mines, and their relative positions and the extent of the mining property belonging to the companies owning them in 1908 are indicated on the sketch map forming figure 7. The ore bodies are included in the contact rock and are associated with large masses of magnetite. They occur along a mineral zone between the diorite intrusive mass and a narrow belt of limestone, which is traceable for about 2 miles from the east side of Mamie Creek westward to Kasaan Bay. This zone ranges in width from 100 to 300 feet, though, because of its flat dip and its conformity with the contour of the mountain slope, it appears locally to be much wider. The ore bodies are locally concentrations of chalcopyrite, generally in masses of magnetite. Though the ore masses discovered are limited both laterally and in depth, continued exploration has generally revealed new ore bodies both in depth and laterally.

The ores from these mines are of low grade, the copper content being almost entirely in the form of chalcopyrite. Besides copper they contain from $1 to $2 in gold per ton. In composition they average about 15 to 20 per cent of silica, 30 to 40 per cent of iron, 4 to 6 per per cent of sulphur, and 10 to 15 per cent of aluminum.

MAMIE MINE.

Situation and development.—The Mamie mine, owned by the Brown Alaska Co., is 1¼ miles south of Hadley, at an elevation of 700 feet, in the central part of Kasaan Peninsula. (See Pl. XX and fig. 7.) The mine workings are connected with the smelter at Hadley by an aerial tram 5,500 feet in length and with the beach by a horse tram 7,700 feet in length. The horse tram is used for transporting supplies. Mine developments in a large way were not begun until 1904. During that year the ore bodies were explored by numerous open cuts, tunnels, and diamond-drill holes. In the following year mining was begun from the open pits and new ore bodies were developed by tunnels and shafts. At the close of 1905 considerable ore was delivered to the smelter, and throughout 1906 the production was large. In 1907 diamond-drill investigations were advanced, new ore bodies were located at greater depth, and the ore production continued with little interruption until late in September. In October all operations were suspended. The total developments up to 1908 consist of 5,000 feet of tunneling, drifting, and crosscutting and about the same amount of diamond-drill prospecting. The smelter or reduction plant at Hadley consists of a blast furnace of 350 tons daily capacity, a sampling mill, coal and coke bins, ore bunkers of 10,000 tons capacity, boiler house, engine house, electric-light plant, and other conveniences. The ores from the Mamie and Stevenstown mines first go through the samplers, next to the ore bunkers by gravity, and thence by gravity to the furnace. The slag from the furnace is granulated and carried by water to the beach. A cable tramway extends from the wharf to bins above the sampling mill, which have been built to receive custom ore. The plant is so arranged that its daily capacity may be doubled if necessary. Smelting operations began December 5, 1905, and in 1906 the furnace was in blast about 20 days each month. In September, 1907, this plant was closed. (See Pl. XXI, *B*, and fig. 8.)

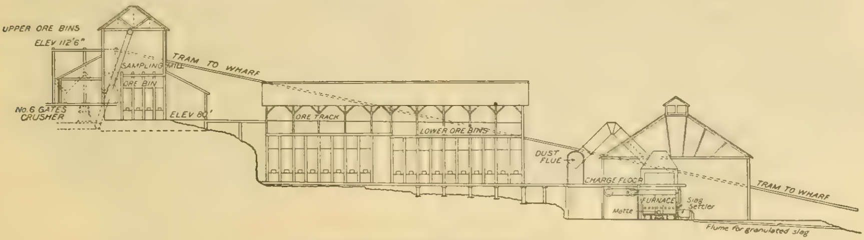


FIGURE 8.—Section of Hadley smelter.

Early in the summer of 1908 the Mamie and Stevenstown mines were consolidated under one management, which obtained a lease of the smelter. The underground workings at the Mamie mine were pumped out and repaired and mining developments were begun. The smelter was reconstructed to treat a larger quantity of ore and was put into operation early in September. The mines and smelter were operated until the first of November, the smelter treating an average of 360 tons daily. The lack of siliceous ores, however, necessitated the suspension of operations at both the mine and smelter. The Mamie mine and Hadley smelter have both been idle since 1908 (1913).

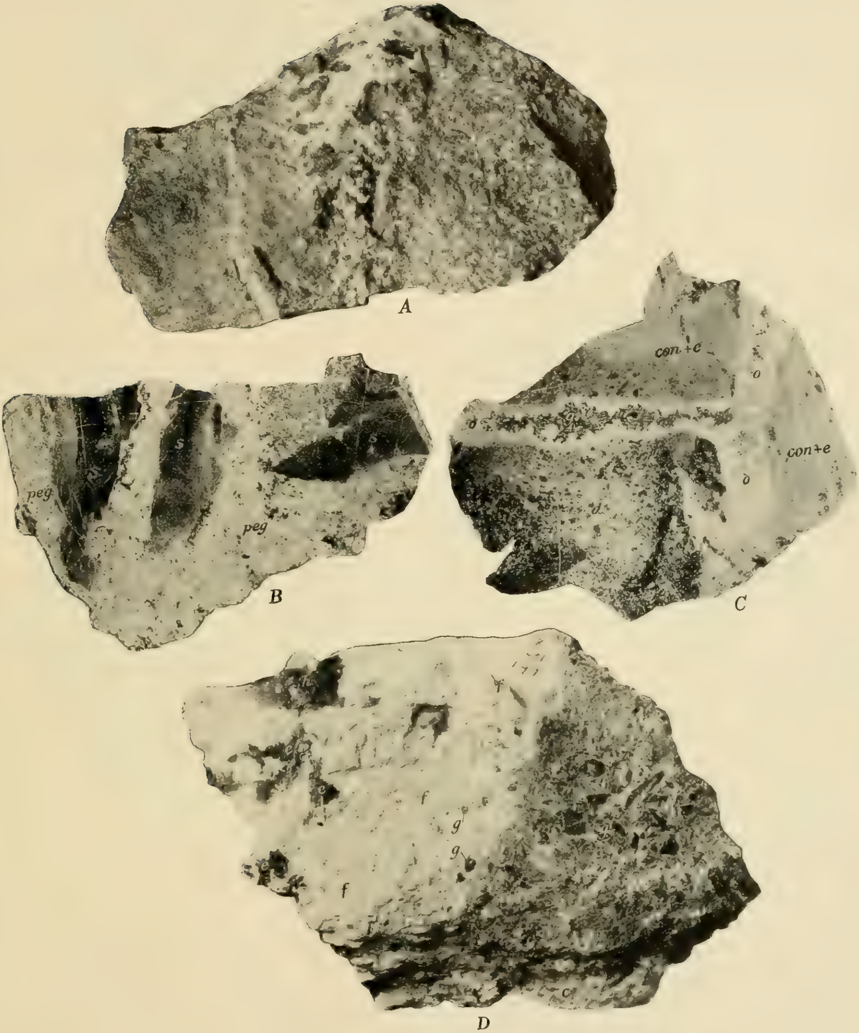
PLATE XVIII.

A. Specimen from Rush & Brown mine, showing contact of diorite with graywacke and development of pegmatite along contact.

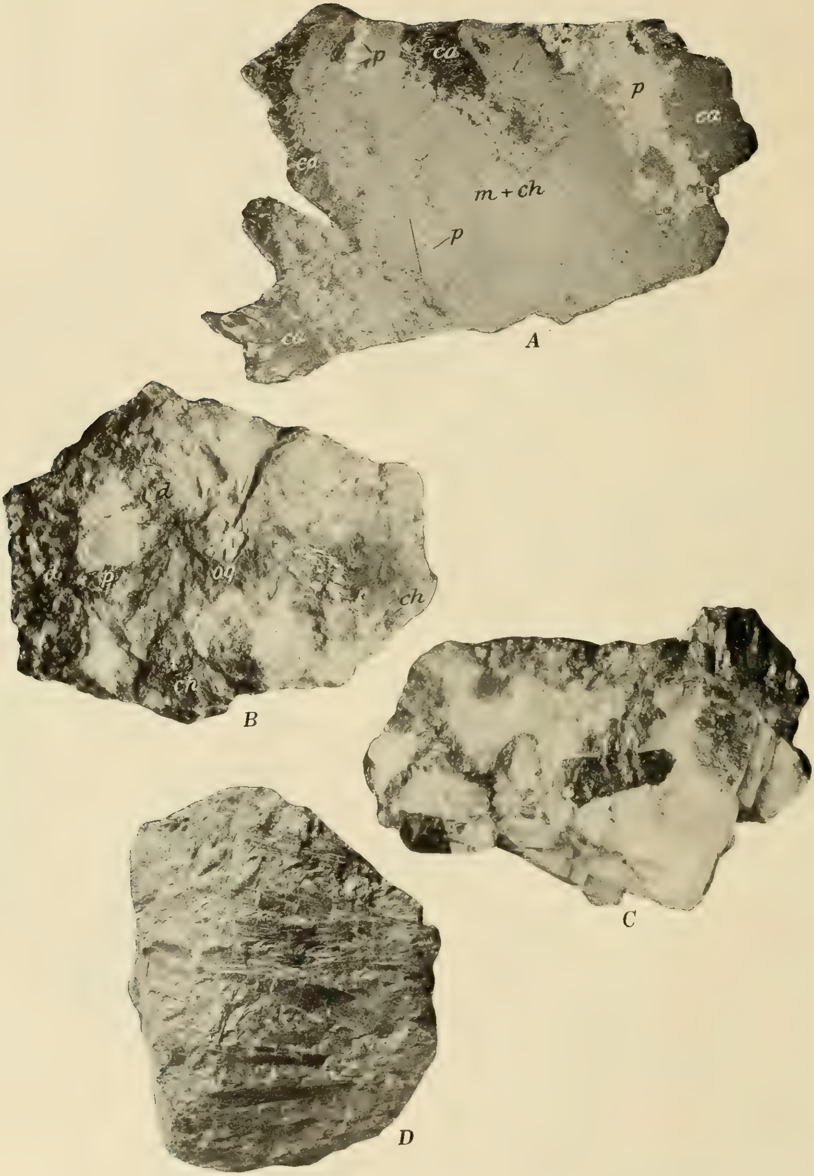
B. Pegmatite phase of diorite, with inclusions of schist; *peg*, pegmatite; *s*, schist.

C. Specimen from Mount Andrew mine, showing orthoclase veinlet cutting altered diorite and entering contact rock; *con*, Contact; *e*, epidote; *d*, altered diorite; *g*, garnet; *o*, orthoclase veinlet.

D. Feldspar dike with epidote cutting contact rock; *c*, calcite; *e*, epidote; *f*, feldspar; *g*, garnet; *h*, fibrous hornblende.



ROCKS FROM MINES ON KASAAN PENINSULA.



ORES AND MINERALS FROM MINES ON KASAAN PENINSULA.

PLATE XIX.

A. Ore from Mount Andrew mine, showing association of magnetite, pyrite, and chalcopyrite in contact rock; *ca*, calcite amphibole rock; *m* + *ch*, magnetite and chalcopyrite; *p*, pyrite.

B. Ore from It mine, showing altered diorite, chalcopyrite, and pyrite in orthoclase quartz contact rock· *d*, diorite; *ch*, chalcopyrite; *p*, pyrite; *oq*, orthoclase and quartz.

C. Ilvaite from Mount Andrew mine.

D. Hornblende with chalcopyrite ore from Stevenstown mine.

Ore bodies.—The ore bodies at the Mamie mine are contact deposits included in a zone 400 feet wide lying between a diorite intrusive mass and a limestone. Within this zone the masses of valuable copper ore are limited either by such a decrease in the copper content of the inclosing rock as to prohibit profitable extraction or by fault planes. Garnet, pyroxene, epidote, hornblende, and magnetite compose the contact rock. Chalcopyrite occurs in small quantities throughout the rock. The ore bodies, or the portions of the contact rock where the copper is sufficiently concentrated to make ore, are irregular masses ranging from 50 to 100 feet in length and from 10 to 40 feet in width, the major axis striking northward. Nine such ore masses are exposed in the mine workings. Some of them are included entirely in masses of magnetite, thus making basic ore; others occur in the garnet-epidote gangue rock, making a siliceous ore. Veinlets of calcite and some of quartz intersect the ore masses, indicating a later period of mineral deposition, though the main ore bodies are believed to have been deposited contemporaneously with the inclosing contact rock. (See Pl. XVIII, *B* and *D*.)

STEVENSTOWN MINE.

Situation and development.—The Stevenstown mine (Pl. XXI, *C*), owned by the Hadley Consolidated Copper Co., is just above and southwest of the Mamie mine, at an elevation of 1,000 feet. (See fig. 7.) From the mine a surface tram 700 feet long connects with the aerial tram at the Mamie mine, over which the ore is transported to the smelter at Hadley. A trail also leads from the mine down the south side of the peninsula to Boggs Landing, on Kasaan Bay, a distance of 1 mile. In 1908 the mine was developed by three "glory holes" or open pits, connected by raises with a 550-foot tunnel that penetrates the crest of the mountain. Actual mining was begun in June, 1905, before which time prospecting had been carried on, and in September, 1905, ore shipments to the Hadley smelter began. A large amount of ore was produced during 1906 and until the first of July, 1907, when mining was suspended. In 1908 operations were renewed and additional output was made and sent to the smelter at Hadley. In the autumn of that year, however, the mine was closed.

Ore bodies.—The ore bodies on the Stevenstown property correspond both mineralogically and genetically with those at the Mamie mine. They occupy a relatively flat position on the crest of the mountain ridge and are apparently underlain by the monzonite intrusive which forms the footwall of the mineral belt and which is exposed throughout the tunnel that penetrates the mountain top. The hanging wall as well as a large portion of the ore bodies on this property have been removed by erosion and the contact zone is only 20 to 40 feet in width instead of 200 to 400 feet, the width on the Mamie property just below. Strata of limestone and of greenstone tuff lie northeast of the ore bodies and continue westward toward the Mount Andrew mine, forming the hanging wall of the mineral zone.

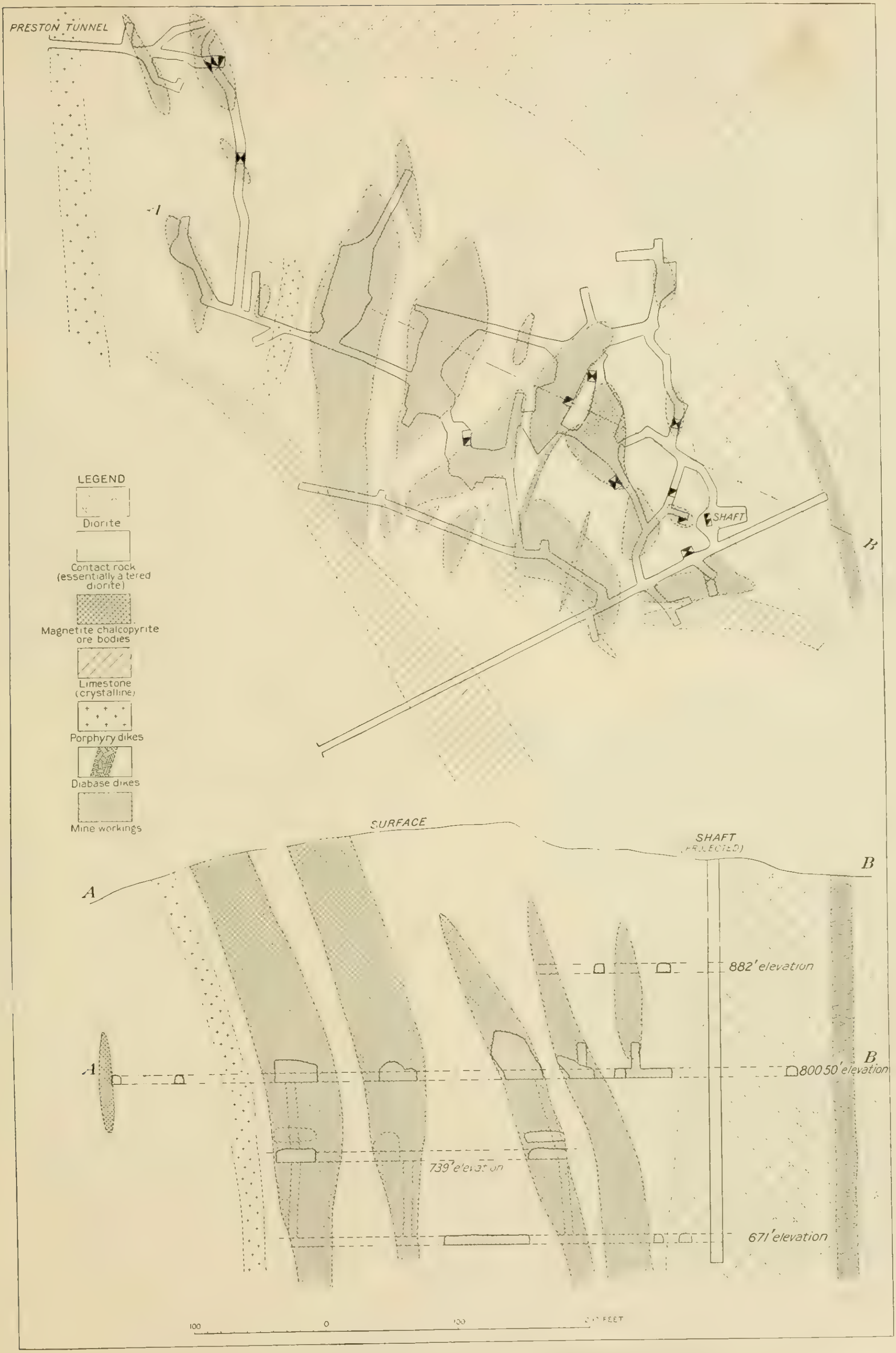
The mine workings are all surface pits connected by raises with the main tunnel and have developed several relatively flat-lying ore masses. These masses are included within an area measuring 350 by 200 feet, the pits being 20 to 40 feet deep. The central portion of this area is traversed from north to south by a 40-foot felsite dike, which is of later intrusion than the syenite and crosscuts the ore body. Smaller dikes of diabase and basalt, 1 foot to 5 feet in width, crosscut the ore bodies and country rock at several points in these mine workings.

The ore is chiefly magnetite, chalcopyrite, and pyrite associated with hornblende and calcite, all included in a more or less banded garnet-epidote gangue. (See Pl. XIX, *D*.)

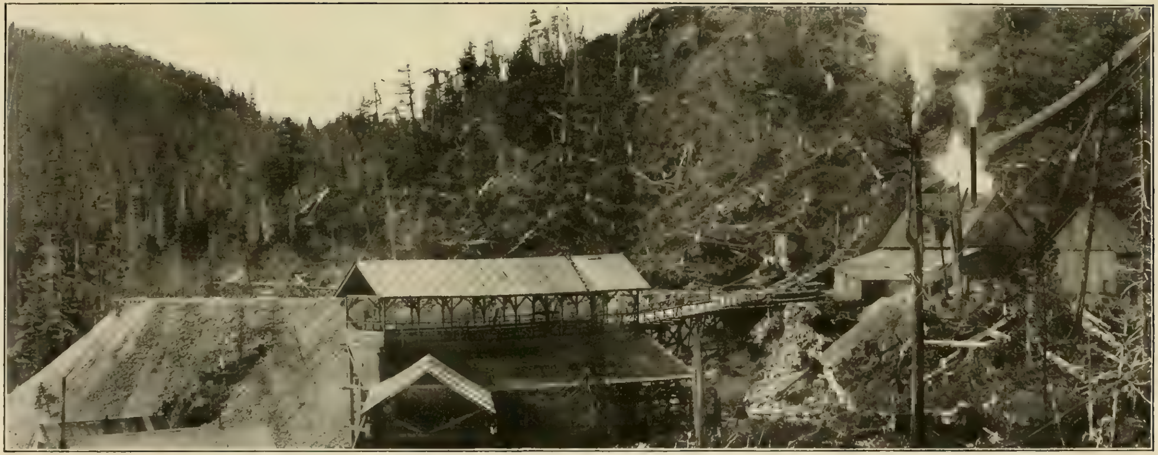
Surface oxidation has produced considerable limonite and some malachite and azurite; small particles of native copper also occur along slipping planes, though these secondary minerals are relatively unimportant.

MOUNT ANDREW MINE.

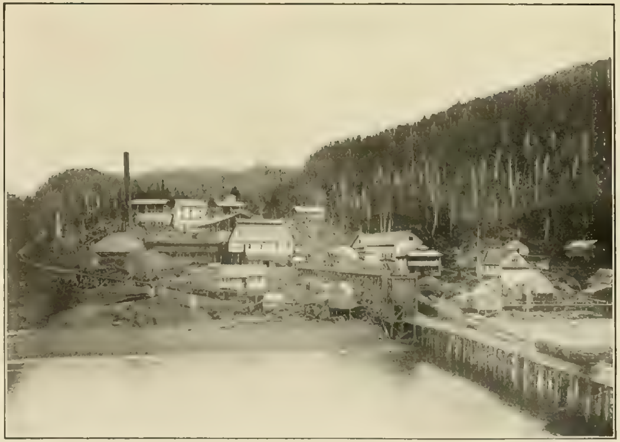
Situation and development.—The Mount Andrew mine workings are three-fourths of a mile from Mount Andrew landing, on the southwest side of Kasaan Peninsula, and one-half mile west of the Stevenstown mine, at an elevation of 1,400 feet. A cable tramway 3,600 feet long leads from the mine to the ore bunkers and wharf at Mount Andrew landing.



PLAN AND SECTION OF WORKINGS OF MAMIE MINE IN 1908.



A. SURFACE WORKINGS OF MAMIE MINE IN 1908, SHOWING TRAMWAY TO STEVENSTOWN MINE.



B. HADLEY SMELTER.

C. WORKINGS OF STEVENSTOWN MINE IN 1908.

This mine is developed (1908) principally by a tunnel 620 feet long, which undercuts the ore bodies at depths of 60 to 100 feet or more. From this tunnel several hundred feet of drifts and crosscuts have been driven, and upraises have been carried through the ore bodies to the surface. The ore is mined from large underground stopes and from surface pits or glory holes and is delivered through chutes at tunnel level to the ore bunkers at the head of the aerial tram and thence carried to the wharf, where it is loaded for shipment. Developments in a large way were not begun until late in 1905, and during 1906 the aerial tram was erected, the wharf built, the compressor plant installed, and considerable ore developed. The first ore shipments were made in October, 1906, and production continued until October, 1907, when operations were suspended.

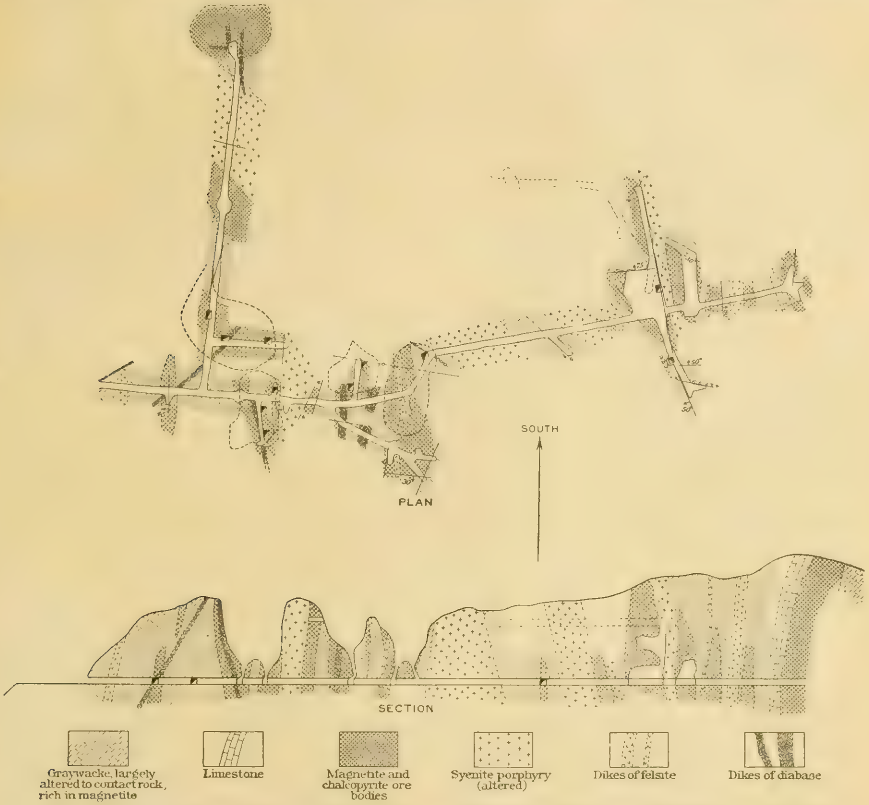

SOUTH
PLAN
SECTION
Graywacke, largely altered to contact rock, rich in magnetite
Limestone
Magnetite and chalcopyrite ore bodies
Syenite porphyry (altered)
Dikes of felsite
Dikes of diabase

FIGURE 9.—Plan and section of workings of the Mount Andrew mine (1908). This illustration is diagrammatis and generalized.

In 1908 the mine was not operated. In 1909 operations were renewed under the management of the proprietary corporation, the Mount Andrew Iron & Copper Co., and from March until late in the autumn a steady output was maintained. During the winter of 1909 developments were continued and additional ore reserves were opened. Shipments began again early in the spring of 1910 and the usual annual production was recorded for that year. The most noteworthy development work undertaken in 1910 was that on the new 1,600-foot adit tunnel, which starts at the old camp and is projected to undercut the ore bodies 300 feet below the present working levels. (See fig. 9.) In 1911 the mine continued producing, though its output was somewhat less than in former years.

Ore bodies.—The ore deposits on this property are included in the same mineral belt as those at the adjacent Mamie and Stevenstown mines, with which they are in every way comparable. Six ore bodies, consisting of irregular masses of magnetite-chalcopyrite associated with the garnet-epidote contact rock, have been developed and have been mined to a considerable extent. These bodies of ore are 10 to 50 feet wide, 40 to 80 feet long, 100 feet or more in depth, and have a general northerly strike and pitch. They are separated by barren areas of contact rock and dikes 20 to 60 feet wide of altered syenite porphyry. (See Pl. XXII, *A*, and fig. 9.) The mine workings consist essentially of surface pits which are undercut by a crosscut tunnel running east and west. This tunnel, with connecting drifts and raises, includes 2,200 feet of underground developments. Numerous gouge seams and slickensides, indicating faulting, were observed in the mine workings, and some of the ore bodies were laterally displaced 1 foot to 6 feet. Dikes of diabase and felsite, from 2 to 12 feet wide, crosscut the ore bodies and country rock in various directions and were evidently intruded after the ore deposits had been formed. (See Pls. XVIII, *C*, and XIX, *A* and *C*.)

At other points on Mount Andrew large masses of the magnetite carrying an amount of copper insufficient to make a copper ore have been formed. These deposits, though not valuable for their content of copper alone, may sometime be a source of iron.

MINES AND PROSPECTS NEAR KASAAN BAY.

TYPES OF DEPOSITS

Along the northeast shore of Kasaan Bay there are a number of copper prospects and one producing mine. Two types of contact deposits were recognized. One type, at the contacts of diorite masses, is represented by the It mine and the Alarm, Haida, and Copper Center prospects; the other type occurs at the contacts of dikes of syenite porphyry and diorite, and is represented by the Uncle Sam, Ouray, and Copper Queen prospects. The deposits of the first type are concentrations of chalcopyrite ore in the contact rock between the diorite and either the limestone or the graywacke. The bodies of minable ore are from a few feet to 25 feet or more in thickness and are generally more siliceous and richer in copper than those at the Mamie and Mount Andrew mines. The ore bodies along the syenite porphyry dikes contain rich ore here and there, but have added little to the copper production of the peninsula.

IT MINE.

Situation and development.—The It Mining Co. was organized early in 1908 and acquired what were formerly known as the Taylor prospect and the Eagle's Nest group. These prospects are 4 miles northwest of Kasaan, 4,000 feet from the shore line, at an elevation of 400 feet. They were developed to some extent in 1907 by the Sea Island Copper Mining Co., but reverted to the original owners, who sold them to the It Mining Co. Development work was begun by this company in May, 1908, and by the end of September a surface tramway 1 mile long and a wharf were completed, and in October of that year ore shipments were begun. In 1909 the mine was a steady producer and development work was advanced. A compressor plant was established near the wharf and a hoisting engine was installed at the mine. From the short adit level a shaft 50 feet deep was sunk and about 250 feet of development was done at this new level. In 1910 two other levels at depths of 100 and 150 feet were driven, and the ore production was maintained as in former years. Some prospecting was done by diamond drilling. In 1911 a 1,400-foot tunnel was begun, which is projected to undercut the ore deposits at a depth of 500 feet.

The ore from this mine is siliceous and contains little or no magnetite. The gangue is sorted by hand, the product being thus made richer before shipment. (See Pl. XIX, *B*.)

Ore bodies.—The ore bodies are contact deposits which lie on both sides of a diorite intrusive mass. (See Pl. XIX.) The contact zone here is widest on the northeast side of the diorite, where the principal ore bodies are found, though developments on the southwest side have also revealed small masses of ore. The intruded rocks are limestone and graywacke and have been much altered by infiltration of minerals from the contact zone.

The minable ore bodies consist of chalcopyrite, pyrite (often in large octahedral crystals), garnet, epidote, and some hematite. They are from a few feet to many feet in dimensions. Several such bodies have been found and mined and exploration, both in depth as well as laterally, continues to expose masses of ore.

UNCLE SAM MINE.

Situation and development.—The Uncle Sam mine, originally called the White Eagle group, lies 3 miles northwest of Mount Andrew landing and one-half mile from Kasaan, on the south slope of Kasaan Peninsula. (See fig. 10, p. 96.) The mine workings are 430 to 550 feet in elevation and less than half a mile from the beach. Mining operations have been advanced on this property at intervals since its discovery in 1899, and in 1901 an aerial tram, ore bunkers, and a wharf were built. Early in 1906 a shipment of ore was made, but no further work was done until March, 1907. At that time operations were renewed, continuing until July, when another ore shipment was made. The mine is developed (1908) by a tunnel and drifts, amounting to about 800 feet in length, and by open pits exposing the ore body on the surface above the tunnel. From this working tunnel a surface tram 1,150 feet long conveys the ore to the wharf. This mine has now (1912) been closed since the autumn of 1907.

Ore body.—The ore body exposed in the tunnel is an irregular lens of chalcopyrite-pyrite ore 6 to 8 feet in width, striking north and pitching about 45° N. It is cut off to the north by an east-west fault dipping 80° N., which shows but a small amount of gouge. At the open cut above the tunnel similar masses of ore are exposed, but no large ore bodies have been discovered. Garnet, epidote, magnetite, and calcite occur as gangue minerals and in many places form small geodes. The chalcopyrite ore contained in this gangue rock is irregularly distributed in small masses and not along well-defined lines. The country rock is made up of strata of chloritized and epidotized greenstone tuff, which are underlain by the intrusive syenite and are cut cross by small dikes of diabase of later origin than the ore bodies.

COPPER QUEEN GROUP.

The Copper Queen group of claims, which represents the first copper locations on Prince of Wales Island, lies about one-half mile southeast of Kasaan. In 1898 these claims were sold to the Kasaan Bay Mining Co., which made additional locations. Small operations were in progress from 1899 until 1902, and 500 feet of tunneling was done, besides surface excavations. Since 1903 the property has been idle.

The principal ore deposit is exposed along the side of a gulch at a point 300 feet in elevation. It consists of an irregular mass of chalcopyrite ore accompanied by pyrite and magnetite in a garnet-epidote gangue, at the contact of an altered intrusive syenite with the greenstone tuff. Below these exposures a crosscut tunnel 400 feet in length has been driven in the altered syenite, but has failed to reveal any ore.

Other mineral exposures occur on these claims at points close to tidewater and have been prospected by shafts and open cuts, but so far no important deposits have been discovered. Practically no work has been done on this property for several years (1912).

POOR MAN'S GROUP.

The Poor Man's group of two claims is 2 miles northwest of Kasaan. In 1908 the mine workings were connected with deep water by a surface tramway and wharf having a total length of about 2,000 feet. The principal developments are at the head of the tramway and consist of a tunnel, driven 90 feet in a southwesterly direction, which crosscuts a 40-foot body of magnetite ore and 30 feet of garnet-epidote contact rock, and at its face enters a wide dike of red syenite for 20 feet. At a point 80 feet from the mouth of the tunnel is a vertical shaft extending 30 feet to the surface and 60 feet in depth. This body of magnetite is exposed on the surface above the tunnel, and similar masses have been prospected by short tunnels and cuts and

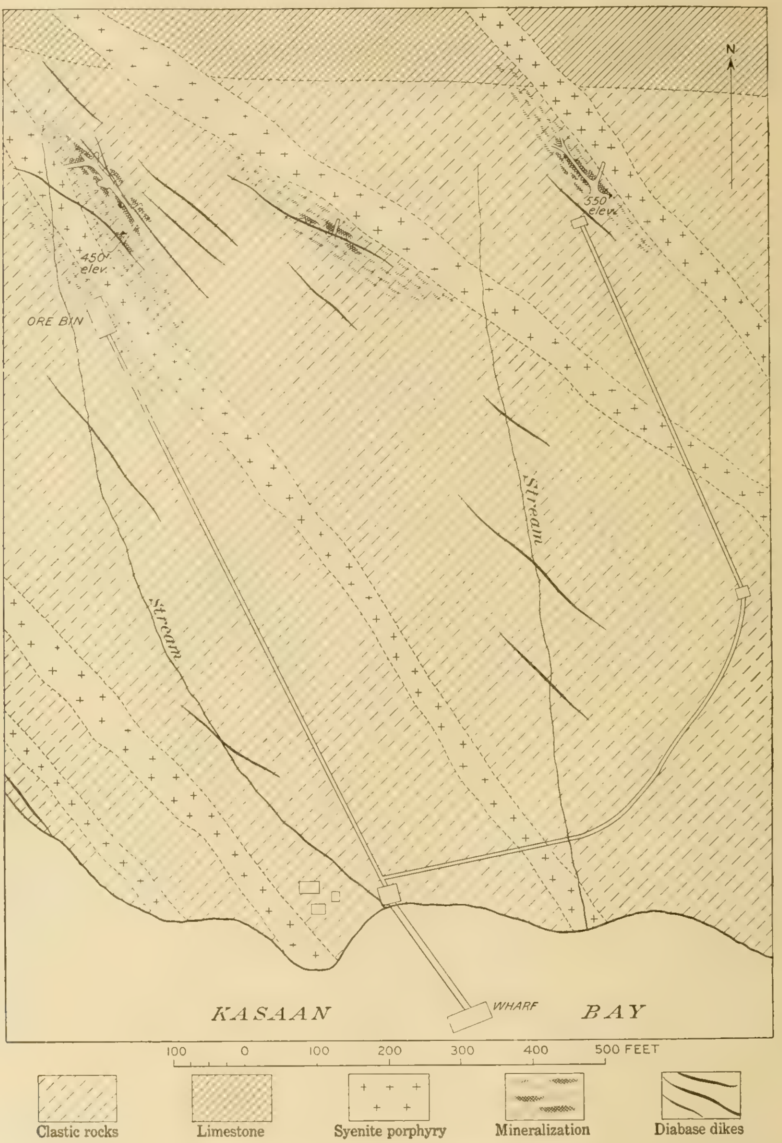


FIGURE 10.—Plan of workings of the Uncle Sam mine (1908).

shafts at points along the tramway and on adjoining properties. Associated with the magnetite are large amounts of calcite and hornblende and some pyrite, chalcopyrite, garnet, and epidote. Although the magnetite deposit itself is extensive, the chalcopyrite ore occurs only in isolated pockets or narrow veinlets and is not disseminated throughout the magnetite in sufficient amounts to make a copper ore of the entire body. It is noteworthy, however, that these ore bodies may be of value for their iron content. Minor displacements, due to faulting on slipping planes, and dikes of diabase and felsite crosscutting the deposits were noted.

BROWN & METZDORF PROSPECT.

The Brown & Metzdorf prospect is one-half mile from Kasaan Bay, at an elevation of 310 feet. The ore body is a mineralized mass of garnet rock carrying chalcopyrite and pyrite. It is exposed for a width of 10 feet, showing a banded structure, and evidently replaced the bedded quartzite and greenstone tuff country rock. A wide belt of limestone is exposed in bluffs along the trail just below this prospect.

PEACOCK AND TACOMA CLAIMS.

The Peacock and Tacoma claims are about 3 miles southeast of Kasaan. The Tacoma claim extends to the beach, where open cuts have been made on ore exposures that are covered at high tide. The ore is confined to a garnet-epidote rock and occurs in irregular patches or finely disseminated particles. In the cuts on the beach a small amount of ore is exposed, and above it, at an elevation of 50 feet, a tunnel 60 feet long (1908) enters the hill in a northeast direction. This tunnel crosscuts a wide belt of garnet-epidote rock containing some chalcopyrite. Other open cuts expose small amounts of ore at several places, but no large ore masses have been developed.

The Peacock claims adjoin the Tacoma claim on the north and extend to the center of the peninsula. At 600 feet from the beach and 120 feet above tide a tunnel 45 feet long exposes a belt of garnet-epidote contact rock containing magnetite and a small amount of chalcopyrite. Still higher, at 325 feet, a second tunnel 30 feet long, following the contact of a diabase dike, exposes a smilar mineral-bearing rock. Here also dikes of felsite and basalt occur, and slipping planes displace the mineral body in various directions. The amount of development on these properties has not been sufficient to disclose ore bodies large enough to justify mining, but systematic prospecting may open up deposits of value.

HOLE IN THE WALL PROSPECTS.

The small cove known as Hole in the Wall lies on the north side of the harbor at Hadley, and along its shores and west of it a number of claims have been located, among them (in 1908) the Plumley group and the Eureka, Sunrise, Pennsylvania, Venus, and Pelaska claims. On the Hilma claim of the Plumley group, at a point one-half mile northwest of the head of the cove and 310 feet in elevation, a tunnel 25 feet in length has been driven along the contact of an altered limestone belt with a dioritic batholith, in which small masses of chalcopyrite are exposed in a garnet-epidote-calcite contact rock. On the Eureka claim, at tidewater, similar contact deposits are being developed and are reported to be of considerable extent. The Sunrise claims, three in all, are west of the Hole in the Wall, and on these claims at points along a gulch small ore masses replace limestone beds at or near their contact with granodiorite. At an elevation of 1,050 feet this contact aureole is 25 feet wide and contains considerable magnetite and chalcopyrite ore, which shows much surface alteration. On the south slope of the hill, at an elevation of 950 feet, is an open cut exposing a highly crystalline marble, slightly banded, striking N. 65° E. and dipping 60° NW. This marble overlies the contact rock, which carries small amounts of the copper ore. On the Pennsylvania claims, southeast of the Sunrise claims, an open cut following a felsite dike at an elevation of 850 feet exposes a small vein 2 to 3 feet wide consisting of pyrite with small amounts of chalcopyrite. The prospects on the Venus claims show contact deposits similar to those exposed on the Sunrise claims to the north and are apparently along the same intrusive contact. The Pelaska claim, extending from the head of the cove westward, has been developed by a tunnel over 100 feet in length following a belt of altered limestone intruded by a diabase dike, along which occurs garnet-epidote contact rock carrying some chalcopyrite. This deposit is interesting geologically, but the amount of ore exposed is small.

MINES AND PROSPECTS AT THE HEAD OF KASAAN BAY.

LOCATION.

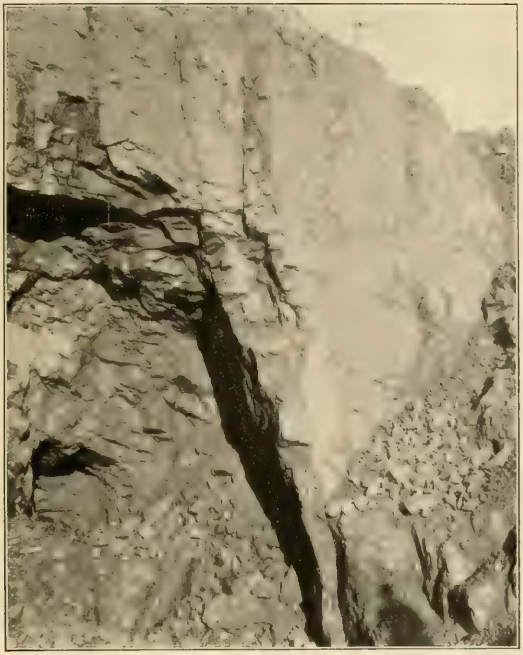
The head of Kasaan Bay includes the entire northwest extension of Kasaan Bay. It is a relatively shallow embayment 3 miles in width, including a number of low wooded islands and shoals, and affording several good anchorages. The adjacent land area is low and is occupied by a "salt chuck" 2 miles in length and by three small lakes. To the southwest is a mountain range including Granite Mountain and other rounded summits less than 4,000 feet in elevation, and to the northeast is a low ridge of hills forming the divide between Kasaan and Thorne bays. The principal mines in the immediate vicinity are the Rush & Brown mine and the Venus group to the northwest and the Goodro claims to the northeast. In 1901, when A. H. Brooks visited this section, none of these properties had been located, and not until 1904 were the copper-bearing ore bodies discovered.

The area is occupied principally by stratified rocks ranging from a fine tuff to a coarse conglomerate, and in places showing a development of large hornblende crystals. These bedded rocks are invaded by granodiorite masses, and dike rocks of various composition intrude both the granodiorite and the bedded rocks. The copper ore occurs (1) at the contacts of the granodiorite with greenstone tuff, conglomerate, and limestone, as at the Rush & Brown mine; (2) along shear zones in the greenstone tuffs and conglomerates, as at the Venus group and Rush & Brown mine; and (3) in small masses and disseminated particles scattered irregularly through an altered basic diorite, as at the Goodro claims.

RUSH & BROWN MINE.

Situation and development.—The Rush & Brown property includes (1908) eight claims extending from the "salt chuck" northwestward, the principal mine workings being located on the Iron Cliff claim, at an elevation of 300 feet, about 2 miles from the wharf at the head of the bay. (See fig. 11.) In 1904 this property was prospected by long trenches and open cuts, and a shaft 25 feet deep was sunk on the ore body. In 1905 it was leased by the Alaska Copper Co. and a new shaft was started 120 feet south of the old shaft and sunk to a depth of 84 feet. From the bottom of this shaft the principal ore body, the magnetite deposit, was developed by drifts and crosscuts and a drift was extended to a second ore body, the sulphide deposit, 160 feet farther northeast. In 1907 the shaft was sunk an additional 93 feet and another level was started. The ore from the mines is transported by a gravity tram to ore bunkers one-fourth mile below the mine and thence by a railroad 2¾ miles long to the wharf at the head of the bay, where ore bunkers of 2,000 tons capacity have been built. During 1906 ore was shipped to the smelter at Coppermount, and in 1907 shipments were made to the Tyee smelter at Ladysmith, British Columbia. The mine was practically idle during 1909–10. In 1911 work was again renewed and since then shipments of ore have been continued.

Ore bodies.—In 1908 two ore bodies had been developed at the Rush & Brown mine. One is a contact-metamorphic deposit consisting of a copper-bearing magnetite body, developed to a length of 100 feet and a width of 30 feet, in the contact-rock gangue lying between diorite and an altered graywacke, the line of contact striking nearly east and west. The other deposit, 160 feet to the north, occupies a shear zone in the greenstone tuff and conglomerate beds and is a sulphide body composed of chalcopyrite and pyrite in a gangue of altered graywacke and quartz and calcite. It is developed to a width of 4 to 14 feet and in 1908 had been followed for a length of 85 feet. The mine management in 1913 reported that the sulphide ore body on the second level was cut off by a fault but was picked up again and explored for a distance



A. PORPHYRY DIKE CUTTING ORE BODY NO. 4, MOUNT ANDREW MINE.

B. ENTRANCE TO SLOPE AND SURFACE CAPPING OF ORE BODY AT RUSH & BROWN MINE.

Photograph taken in 1908.

of 170 feet beyond the fault. The strike of this sulphide deposit is northeastward and its dip is 60° SE., toward the larger deposit. Further exploration will doubtless disclose other ore bodies of the same types. (See Pls. XVIII, *A*, and XXII, *B*.)

GOODRO MINE.

The Goodro mine, also known as the Joker group, is half a mile from the head of the salt chuck entering Karta Bay. The surrounding area is relatively low, the claim being located on a knoll about 400 feet in elevation. The copper deposit at this mine consists of disseminated sulphide ores in a gabbro intrusive belt, which is shown on the geologic map (Pl. XV). At the time of the writer's visit this deposit had been developed by surface pits, an open cut 70 feet long, and a tunnel 125 feet long, which crosscuts the deposit 90 feet below the surface and 90 feet from its mouth. In 1909 a wharf, ore bins, and 3,850 feet of tram (in part gravity and in part horse tram) were constructed, and the shipment of ore was begun. The ore was lightered out of the salt chuck on barges at high tide and loaded on vessels lying at the head of Kasaan Bay. In 1910, after the winter shutdown, operations were again resumed. A winze 100 feet deep was sunk from the main tunnel level, and from its bottom drifts were extended to the east and west 150 feet in length. The winze is said to have been sunk in ore for 45 feet. At the lowest level 14 feet of ore, consisting of disseminated chalcopyrite and bornite in the gabbro, is said to have been crosscut. In 1911 only assessment work is reported to have been done on this property.

The ore deposit at this mine is of special interest because bornite is the dominant metalliferous mineral, and it is the only locality in southeastern Alaska where bornite has been found in quantity. The ore occurs in small masses and disseminated particles associated with epidote, feldspar, and biotite, minerals that largely replace the inclosing gabbro. Native copper, chalcocite, chalcopyrite, and small amounts of gold are also associated with the bornite. The mineralization of the gabbro with bornite is exposed across a width of 60 feet and for a length of 100 feet or more. Other smaller deposits of bornite in the gabbro were noted on adjacent properties.

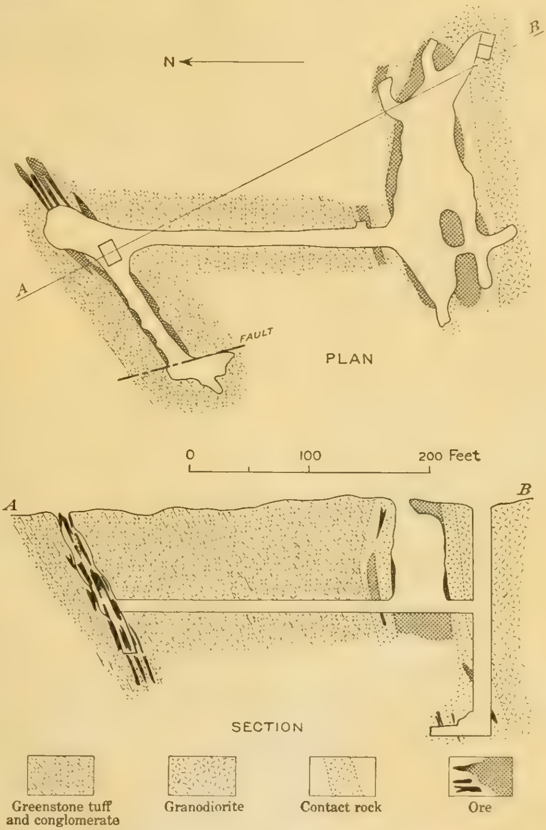


FIGURE 11.—Plan and section of the Rush & Brown mine (1908).

MAMMOTH GROUP.

The Mammoth group, including the Haida mine, lies on the east side of Kasaan Bay, about 6 miles from Kasaan and one-third of a mile from tidewater on the top of a low hill 500 feet in elevation. The property was largely developed in 1904–5 by the original owners, and in June, 1906, was sold to the Haida Copper Co., which began active developments and made plans for erecting a gravity tram 2,000 feet in length, extending to the beach, and a wharf and ore bunkers. In April, 1907, these improvements were completed and the company made shipments of ore to the Hadley smelter. Early in the summer, however, operations were suspended, and the mine has since been idle. The mine is developed by a tunnel 120 feet in length, connecting with a shaft 35 feet deep, which in turn connects with a surface pit on the ore body. In 1908 exploratory drifts had been extended from the tunnel, and prospect pits and short tunnels have been driven at other points on the property. Little work has been done at this prospect in recent years.

The ore body is an irregular magnetite mass carrying chalcopyrite in a gangue of garnet and epidote. The country rock in the immediate vicinity is made up of greenstone tuff and conglomerates, though just below the mine workings a belt of intrusive diorite is exposed which forms the western half of the ridge and probably underlies the ore body. The deposit is developed by an open pit over an area about 50 feet in diameter. This is undercut by a tunnel at a depth of 30 feet, and though the magnetite is exposed at this depth, chalcopyrite is not so abundant. To the northeast the ore body is limited by a fault plane striking nearly east and west and dipping 75° S. Other slipping planes striking at different angles were noted in the ore body and inclosing rock.

COPPER CENTER PROSPECT.

The Copper Center group of claims lies 1 mile north of the Mammoth group at an elevation of 400 feet. It was located in April, 1907, and in July was bonded to mining men who undertook its development. In 1908 several shafts from 10 to 30 feet deep had been sunk within an area 300 by 120 feet. In all these shafts and surface cuts magnetite and chalcopyrite ore associated with garnet-epidote and hornblende gangue is exposed. The deposit is apparently flat lying, though the amount of work done is hardly sufficient to prove that it does not continue in depth. It is also probable that further investigations at a greater depth will reveal deposits at other points on the property. The country rock is largely conglomerate and greenstone tuff, underlain by granodiorite, which is exposed down the hillside to the southwest. The area is densely covered by undergrowth, which renders prospecting difficult. The dip needle has been successfully used within this area, and the deposit just described was located by it.

CHARLES PROSPECT.

The Charles property is about 1 mile southeast of the Mammoth group and 5,000 feet from tidewater, at an elevation of 380 feet. It was located in May, 1907, and only a small amount of work has been done on it. The mineral body exposed in a cut 20 feet long and 10 feet deep consists of chalcopyrite masses associated with some magnetite in a garnet gangue which replaces the greenstone tuff country rock. Diorite occupies the hill just west of this prospect, but was not exposed near the mineral body. Dikes of diabase crosscut the ore body and are evidently of later origin. Besides the copper, the ore is said to carry high values in both gold and silver.

VENUS GROUP.

The Venus group of claims is on Iron Creek 1¼ miles from the head of Kasaan Bay and about 1 mile south of the Rush & Brown mine. This property was located in 1904 and a magnetic survey made. Within the area of maximum attraction a pit was sunk and a trench 50 feet in length was made through the overlying débris, exposing the magnetic deposit. Below these surface excavations, which are at an elevation of 250 feet, a tunnel 75 feet in length has been driven which crosscuts 50 feet of débris and 25 feet of country rock, and at its face exposes ore. The country rock is an indurated greenstone tuff with interstratified quartzite beds, the ore occupying a shear zone. Associated with the ore are considerable sphalerite and pyrrhotite, with quartz and calcite as gangue minerals.

PROSPECTS ON TOLSTOI BAY.

CHARACTER OF THE ROCKS.

On the north coast of Kasaan Peninsula, adjacent to Tolstoi Bay, which affords good anchorage, much prospecting has been done and numerous locations have been made, but none of the properties have been developed beyond the prospect stage. The small promontory here is composed largely of the diorite intrusive masses, which are exposed at Tolstoi Point and along the eastern slope of Tolstoi Mountain. On the western slope and along the east shore of Tolstoi Bay greenstone tuff, sandstone, and conglomerate and a few strata of limestone are exposed. Both the bedded and the intrusive rock masses are crosscut by dikes of porphyry and diabase. The ore bodies are contact-metamorphic deposits similar to those at the mines in the southern part of the peninsula. They are lenticular masses of magnetite carrying chalcopyrite and associated with garnet, epidote, calcite, and quartz, inclosed in the bedded rocks near the intrusive granodiorite contact.

IRON CAP GROUP.

The Iron Cap property, also known as the Mahoney group, consists of two claims on the northwest slope of Tolstoi Mountain at an altitude of 1,000 feet, reached by a trail 1½ miles long starting from a cove 2 miles southwest of Tolstoi Point. In 1901 the property was prospected to a considerable extent by open cuts along a gulch and by several hundred feet of diamond-drill holes, but since that time it has been idle. The country rock consists principally of greenstone tuff and a fine conglomerate intruded by syenitic dikes of considerable width, which are apparently related to the ore deposits. Three ore bodies have thus far been located, the largest 20 feet wide and traceable for 50 feet, the major axis striking N. 45° W. A second ore body, separated from the first by a 30-foot dike of altered syenite, is 12 feet wide and is limited on the footwall side (to the southwest) by a fault plane showing a considerable seam of gouge; toward the hanging wall it grades into a garnet-epidote contact rock. The third ore body, which lies just above the other two at an elevation of 1,080 feet, appears to be a flat-lying magnetite deposit only a few feet thick.

WALLACE GROUP.

The Wallace group includes four claims on the southeast slope of Tolstoi Mountain at elevations between 800 and 1,600 feet. At several places on this property small scattered masses of copper ore are exposed, but at no place have the explorations been sufficient to determine the extent of these deposits. The uppermost ore bodies found have been opened by a short tunnel which exposes a vein of garnet-epidote rock containing chalcopyrite. This vein strikes N. 15° W. and dips 20° SW. The lower openings expose a magnetite-chalcopyrite ore, but the bodies do not appear to be extensive.

TOLSTOI GROUP.

The Tolstoi group of claims is south of the Wallace group, just below the summit of Tolstoi Mountain. The ore bodies are low-grade magnetite-chalcopyrite masses similar to those on the Iron Cap group, but they have not been so extensively prospected. Only the required annual assessment work has been done on this property.

BIG FIVE CLAIM.

The Big Five claim lies half a mile east of Tolstoi Bay, on the trail to the Iron Cap group, at an elevation of 370 feet. In 1908 a tunnel 50 feet long and a shaft exposed scattered masses of chalcopyrite, pyrrhotite, and pyrite, in a gangue of garnet, epidote, and calcite. The mineralized mass is 10 feet wide and is a replacement deposit in limestone. Many slipping planes marked by gouge seams traverse both ore body and country rock. Assessment work only is done on this claim each year.

IRON ORE.

The only iron ore found in Kasaan Peninsula and the Copper Mountain area is magnetite, which occurs in large bodies along contacts of diorites and limestones. No special study has been made of these deposits, which have been developed only in connection with the mining of the copper ores. In the foregoing descriptions of the copper deposits, however, numerous references are made to the occurrence of magnetite.

The amount of magnetite shown at the surface is very large, and most of the ore is believed to contain no phosphorus or other detrimental impurities. The work at some of the copper mines has exposed a considerable quantity of magnetite, which carries from one-half to one and a half per cent of copper but which can not now be mined profitably as a copper ore. If the iron could be utilized, however, the copper, which could be separated magnetically after crushing, would furnish an additional source of profit. The utilization of these iron ores would seem to be a metallurgical problem, as there can be no question that they occur in quantities that should make them commercially valuable.

GENESIS OF THE ORES.

GENERAL PRINCIPLES.

In considering the probable source of the metal-bearing minerals that formed the ore deposits and of the mineral-bearing solutions that brought them from their original source and deposited them, with other minerals, in the fissures in the rocks, it should be remembered that, as in most other problems of this sort, certain theories or hypotheses as regards a supposed underlying igneous magma, the activities of mineral solutions, the precipitation of ores, and the metamorphic agencies and action are based on meager evidence. These hypotheses, however, appear to afford the most probable explanation of the condition now existing. The determination of the origin of an ore deposit is not only of scientific interest but of economic importance, for on this determination the miner must base his conclusions as to the depth to which the workable ore may extend and as to whether the ore will become more or less valuable with increase of depth. In most regions the workable deposits of copper ore are concentrations formed by circulating waters, generally of atmospheric origin, which have leached lean original ores and concentrated them as richer ore bodies in the immediate vicinity. On Copper Mountain and on Kasaan Peninsula, however, only deposits containing original or primary ores are found; few or no secondary ore deposits have been discovered.

The contact deposits are the principal valuable ores in these two areas and as they were formed dirrectly by metamorphic processes a discussion of these processes is necessary.

METAMORPHISM PRIOR TO THE GRANITIC INTRUSION.

The metamorphic changes in the stratified rock in the Copper Mountain area and on Kasaan Peninsula have already been described. Such changes were due primarily to heat, pressure, and solution and probably were intensified by the overburden of rock strata that has since been removed by erosion and by mountain-building forces or shrinkage of the earth's crust that caused lateral compression and folding of the beds. These forces produced what is known as regional metamorphism, causing a partial crystallization of the limestone beds, an induration of the gray-wacke, quartzites, and conglomerates, and a partial recrystallization and the development of schistosity in the more tuffaceous and argillaceous beds.

CONTACT METAMORPHISM.

DEFINITION.

In the districts under discussion the metamorphism of the intrusive igneous rocks and of the rocks they intruded is widespread and the processes that were involved in the changes that occurred are numerous. These complicated phenomena are classed under the term "contact metamorphism," a term that covers the mutual effects of the action on the intrusive and the intruded rocks.

The action of an intrusive mass of molten rock—an action that affects both intruded and intrusive rock—is in part recrystallization and in part replacement by added material. This action has its maximum effect at the contact of the intrusive masses and decreases with increase of distance from the contact.

CAUSES OF CONTACT METAMORPHISM.

Contact metamorphism is due largely to the action of superheated solutions derived from the eruptive magma and forced into the rocks, where it produced recrystallization, generally without notable addition or subtraction of material except in contact deposits, which represent an extreme type of metamorphic action and whose metallic content is supposed to have been contained in the superheated aqueous solutions. The presence of superheated steam or water in eruptive magmas is referred to by Gautier,[1] who makes the following statements:

> Geological observations in all parts of the world show that thermal waters are usually related to ancient or modern volcanoes and that they issue from fissures of the same character as those occupied by metalliferous veins or igneous dikes. * * * [The quantity of water set free when granite is brought to a red heat is at least 25,000,000 to 30,000,000 tons (or 2½ to 3 per cent of its volume) for each kilometer of this rock which is the least rich in water.] Thus the gases which I have extracted from rocks are composed of the same constituents as the volcanic gases. The vapor of water, free hydrogen, and carbon dioxide predominate in both, and both contain carbon monoxide, marsh gas, nitrogen, a little hydrogen sulphide, and traces of cyanogen and of petroleum compounds. This analogy of composition suggests an analogous origin.

Lindgren[2] makes the following statement:

> Turning now to the large class of "epigenetic" deposits in which the metal is of later origin than the surrounding rock and has been introduced by agencies foreign to the rock itself, the first division which should receive attention is that of the contact-metamorphic deposits. In these the ores replace limestones or, more rarely, other sedimentary rocks, their substance is beyond reasonable doubt derived from metallic emanations from intrusive magmas, and their occurrence is closely connected with the actual contact with these intrusives, although they may extend for a couple of thousand feet away from the igneous rock. The deposits which generally contain magnetite and chalcopyrite and which usually are poor in gold and silver were formed at a considerable distance below the surface, probably never less than 1,000 feet, and there is, as far as known, no other limit in the depth at which they can be formed except that the heat must not be so high as to fuse the sedimentary beds.

In another paper on ore deposits and physical conditions Lindgren,[3] writing of ore deposits due to contact metamorphism of sediments by intrusive igneous rocks, says:

> These deposits, which are almost exclusively of metasomatic origin, are apparently caused by replacement of calcareous rocks by very hot solutions given off by the cooling magma. These solutions were probably above the critical temperature and thus really in a gaseous condition.

Spurr[4] writes:

> All rocks contain water, but the molten material contains more than the resulting rock. Most of this water is expelled at the moment of solidification, together with certain gases and a great variety of other materials held in solution. When rocks cool at the surface, the escaping water forms the clouds of steam, highly charged with gases and minerals, which issue from fissures, and when they solidify below the surface the waters and gases may be forced into the inclosing rock, producing that recrystallization and rearrangement of its constituents which is called contact metamorphism.

Kemp[5] makes the following statement in regard to magmatic waters:

> That the floods of lava which reach the surface are heavily charged with them there is no doubt. * * * There is no reason to believe that many of the igneous rocks which do not reach the surface are any less rich, and when they rise so near to the upper world that their emissions may attain the surface we must assign to the resulting waters a very important part in the underground economy.

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[1] Gautier, Armand, The genesis of thermal waters and their connection with volcanism: Econ. Geology, vol. 1, No. 7, pp. 688–697, 1906. Translation by F. L. Ransome of La genèse des eaux thermales et ses rapports avec le volcanisme: Annales des mines, 6th ser., vol. 9, pp. 316–370, 1906.

[2] Lindgren, Waldemar, Ore deposition and deep mining: Econ. Geology, vol. 1, p. 36, 1905.

[3] Lindgren, Waldemar, The relation of ore deposition to physical conditions: Econ. Geology, vol. 2, No. 2, pp. 105–127, 1907.

[4] Spurr, J. E., Relation of rock segregation to ore deposition: Eng. and Min. Jour., vol. 76, p. 54, 1903.

[5] Kemp, J. F., The problem of metalliferous veins: Econ. Geology, vol. 1, No. 3 (December–January, 1905–6) p. 229.

Lincoln,[1] writing on magmatic emanations, makes the following statements:

> Magmas contain certain substances which decompose or interact unless prevented by pressure or cooling. These generators give rise to primary magmatic emanations. Cooling or pressure or both cooling and pressure prevent the complete destruction of the generators, hence igneous rocks contain repressed emanations which may be expelled by heating them to red heat at atmospheric pressure.
>
> Intruded magmas by heating the adjoining rocks induce secondary emanations which consist of part of the potential emanations of these rocks. The ratio of primary to secondary emanations is an unknown quantity.
>
> Magmatic emanations which are expelled as gases and vapors become at the ordinary temperatures of the earth's surface solids, liquids, and gases. The principal gases are carbon dioxide, methane, hydrogen, hydrochloric acid, hydrogen sulphide, sulphur dioxide, nitrogen and oxygen with less carbon monoxide and ethane and a very little hydrofluoric, hydriodic, and hydrobromic acids. Water is the only important liquid, and it makes up a large percentage of the total emanation. The solids are chiefly chlorides and sulphates of the alkalies and alkaline earths and of iron, together with a much smaller quantity of metals and mineralizers.

DEVELOPMENT OF CONTACT METAMORPHISM.

As has already been noted, the intruded rock strata had been subjected to regional metamorphism prior to the intrusion of the igneous masses, which cooled and solidified at a considerable depth below the surface. It is therefore reasonable to suppose that the heat contained in the igneous rock masses at the time of their intrusion was gradually, though extensively, imparted to the intruded rock beds. It is reasonable to assume that while losing their heat both the intrusive and intruded rocks contracted somewhat at their contacts, leaving small open spaces and fissures in the contact zone, which permitted the metamorphic action to extend still farther from the contact. Around the intrusive contacts, especially at points where the line of contact is irregular, many cracks and fissures were formed, and along these local fractures the effects of contact metamorphism are most pronounced. The emanations from the igneous magma or mineralizing solutions ascended along these openings, dissolving and precipitating minerals and forcing themselves outward into the more or less porous wall rocks, where they caused replacement of the original mineral components of the rocks. The deposition of minerals from these solutions is attributed to supersaturation resulting from the decrease in the temperature and pressure of the solutions as they came into contact with colder rocks, but was probably to some extent due to precipitation of elements that entered the solutions on their upward course.

ORIGIN OF ELEMENTS CONTAINED IN MINERAL SOLUTIONS.

Whether the elements contained in the mineral solutions were derived directly from the magma from which the solutions emanated or whether they were derived from the rocks through which the solutions passed is not known, but it is probable that certain elements, such as iron, sulphur, and copper, found in the contact deposits and not in the adjacent rocks, were contained originally in the heated solutions. The lime and magnesia in the contact rock, however, are believed to have been derived by the solutions from the calcareous rocks through which they passed; the silica, alkalies, and alumina which have entered into the composition of the contact rock may, on the other hand, have been leached from the diorite.

METAMORPHIC EFFECTS ON THE INTRUDED ROCKS.

The character and extent of the contact metamorphism of the intruded rocks have been determined by many factors, such as the temperature, composition, depth, size, and form of the intrusive mass and the composition and porosity of the intruded rock strata. Though the results of metamorphism should be similar under similar conditions the amount of alteration varies widely from one point to another along the same contact and is besides dependent on the local development of fractures and fissures in the rocks along which the solutions circulated and produced the alterations noted. Extensive replacement of rock beds at certain localities and practically none at others indicates that the metamorphism is due mainly to the action of mineral solutions that were introduced along the contacts, and not so much to the immediate effects of heat and chemical reactions in the intruded rocks themselves at the time of the igneous intrusion.

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[1] Lincoln, F. C., Magmatic emanations: Econ. Geology, vol. 2, No. 3, pp. 273, 274, 1907.

The mineral solutions penetrated the sedimentary rocks most freely and produced metasomatism most readily along calcareous layers in the strata, completely altering them. In such beds diopside, garnet, epidote, and feldspar were formed, and in some places pyrite, pyrrhotite, and chalcopyrite are scattered through them. Limestone beds that lay at the contact are changed to marble and contain tremolite. Generally the line of contact with the limestone is sharp and is marked by the development of granules of diopside next to the intrusive rock and of tremolite in fine needles in the limestone. The contact rock contains included fragments and small masses of limestone and in places considerable calcite, which may have been formed by solution and reprecipitation of the limestone.

The calcite crystals usually form a matrix including diopside and garnet in irregular grains, and in some places appear to be the last mineral formed.

In the more porous strata, such as the schists and graywackes, there is not the sharp contact between the contact rock and the intrusives, except where the intrusive fills fissures that extend into the contact rock. These rocks appear to have been impregnated with mineralizing solutions which deposited in them garnet, epidote, diopside, feldspar, hornblende, wollastonite, tremolite, calcite, and some quartz, the first four minerals being confined to the contact zone and the last five minerals lying farther away from the contact. To what extent these minerals were formed by metasomatism of the rock beds without addition of material is difficult to determine; nor is it possible to say to what extent new material was introduced by the solutions.

METAMORPHIC EFFECTS ON THE INTRUSIVE ROCKS.

The direct changes caused by the adjacent igneous mass are relatively slight in comparison to the changes caused by the mineral solutions that passed along the contact and impregnated the rocks along the channels they traversed. The changes noted are essentially those of metasomatism and occurred after the intrusive mass had solidified. Greater changes were made in the intrusive than in the intruded rocks. In many places metasomatism caused by the solutions has been so great that the intrusive rock itself is entirely transformed into contact rock. Generally, there is no sharp line of division between the contact rock and the intrusive mass, the two grading into each other. In certain places fissure veins of contact rock enter the intrusive rock, but they do not extend far from the contact zone. The wall rocks around the contacts show here and there a slight veining, a few inches to a few feet wide. These veins are pegmatitic, consisting of large amphibole and plagioclase crystals with some pyrrhotite, diopside, and calcite. The feldspar in the diorite itself has been altered to scapolite, the alteration being attributed to the action of the mineralizing solutions. Where wide zones of contact rock occur the intrusive rock has been most altered and has contributed in large measure the material that makes up the contact rock, as is shown by analyses of the unaltered diorite, of the altered diorite at the contact, and of the contact rock itself, which are remarkably similar for rocks that differ so widely in mineral composition.

The main effects of the contact metamorphism on the diorite have been to change the feldspar (essentially alkaline) to scapolite and the hornblende to diopside and epidote. On passing from the unaltered diorite toward the contact one may note that the granitic texture gradually disappears, the rock assumes a dull and somewhat bleached appearance, the altered feldspar aggregates are separated by pale-green diopside and aggregates of epidote, and finally that the rock seems to be amorphous, of a pale-pink to greenish color, and felsitic in texture. This felsitic rock is made up almost entirely of scapolite, light-green diopside, some epidote in tufted aggregates, garnet in patches (in places connected with veins), and scattered particles of calcite. In the contact rock the original feldspar and ferromagnesian minerals are entirely replaced, though the rock still contains unaltered titanite crystals in considerable amounts, which were originally in the diorite, this occurrence emphasizing the fact that the alteration of the diorite has been extensive and that in certain places, at least, the contact rock is only a replacement of the diorite. The first alteration of the diorite was evidently accompanied by the deposition of pyrite, pyrrhotite, and molybdenite. Diopside seems to occur where pyrite is present and calcite with hornblende accompanies the molybdenite and magnetite.

DEVELOPMENT OF THE CONTACT ROCK.

Microscopic study of numerous specimens of the contact rock shows that it is in part altered wall rock, mostly limestone, and in part altered diorite, and that some of it has been formed by the filling of fissures in these rocks. The interior parts of several specimens of limestone that were included in the contact rock and of ores of the Jumbo mine are a finely granular white limestone containing considerable dolomite, which is bordered by a zone, a few centimeters wide, in which tremolite is abundant, and just outside of this zone is another zone, several inches wide, in which tremolite disappears and diopside is abundant. Garnet may accompany the diopside, and at a distance from the limestone may take its place, passing into a vein deposit with garnet druses. Usually, however, a deep-green amphibole appears at the outer border of the diopside zone, and beyond it the ores, chalcopyrite and pyrrhotite, become abundant, passing into solid masses of sulphide. Much of the rock of the contact zone consists of garnet and diopside with calcite, the diopside scattered and the garnet in part scattered and in part filling fissures.

The following analyses show the chemical composition of the several types of rock found at the Jumbo mine. The analyses were made from chips representing every type.

Analyses of specimens of rock from the Jumbo mine.

	1. Diorite.	2. Altered diorite.	3. Contact rock.	4. Limestone.	5. Garnet.	6. Orthoclasite.	7. Diopside.
SiO_2	59.44	46.57	39.51	0.61	35.18	62.03	55.12
Al_2O_3	17.40	13.51	5.87	.30	5.15	16.39	.40
Fe_2O_3	3.30	2.92	8.54	.48	25.05	.72	
FeO	2.77	2.73	3.40		.40	.86	1.12
MgO	1.81	2.85	5.08	8.00	.09	1.60	18.15
CaO	6.51	19.92	29.42	46.45	33.36	3.60	25.04
Na_2O	4.22	2.33	1.00			1.08	.45
K_2O	3.12	2.52	.64	.22		12.38	.02
H_2O-	.06	.33	.33		.42	.24	.17
H_2O+	.56	.53	.62			.61	
TiO_2	.66	.64	.29			.53	
CO_2	None.	3.40	3.68	44.07			
P_2O_5	.28	.27	.07			.13	
SO_3			Trace.				
S	.02			.06			
MnO	.17	.40	.62	.03			
BaO	.07						
SrO	.05						
FeS_2			.64				
MoS_2		.78					
	100.44	99.70	99.71	100.22	99.65	100.17	100.47

1 to 6 are analyses of rock from Jumbo No. 4 claim. Analysts: 1, 4, George Steiger; 2, 3, R. C. Wells; 5, W. T. Schaller; 6, Chase Palmer.
7 is a published analysis (Dana, E. S., System of mineralogy, 6th ed., p. 359, 1892) of a diopside at a diorite limestone contact at De Kalb, N. Y.

The analyses indicate that in order to derive a considerable part of the contact rock from the limestone by the development of such minerals as are abundant in the contact rock it would be necessary to add much silica, considerable ferric oxide, and some alumina, and to subtract a corresponding quantity of lime and carbon dioxide. It is assumed that solutions passing from the cooling intrusive rock performed these changes. The analysis of the altered diorite shows that it has lost such constituents as have been gained by the limestone and that it has gained much lime and carbon dioxide, constituents that the limestone has lost.

A specimen of the altered diorite at the contact with diopside-garnet-calcite rock had lost all its free quartz and most of its plagioclase, and in place of these it contained abundant calcite, considerable garnet, and much diopside. Its orthoclase was still present in nominal amount. Small patches of molybdenite accompanied the calcite. The molybdenite had clearly been introduced, for it was abundant in the adjacent contact rock. If this rock had lost orthoclase and had gained a little more garnet it could not be distinguished from the contact rock developed from the limestone. The analyses of the diorite, altered diorite, and contact rock show clearly that by subtracting the elements of the alkali feldspar—silica, alumina, and alkali—and adding the constituents of the limestone and of garnet the diorite could be transformed into the contact rock. The less altered diorite in places shows little change except the replacement of plagioclase by scapolite and the introduction of calcite.

Irregular veinlike bodies, which are generally the latest phase of the contact rock, vary in composition from pure garnet and nearly pure diopside to mixtures of orthoclase, calcite, and epidote, with or without diopside and garnet. A specimen from the Sultana claim simulates very perfectly the texture of coarse diabase. It contains long, lathlike intersecting crystals of nearly colorless diopside in a matrix of dark garnet and calcite in small amount in place of the garnet, suggesting that the diopside developed in limestone and that the garnet replaced[1] this limestone. The abundance of orthoclase unassociated with quartz is especially noteworthy. It occurs in very irregular branching masses a few inches wide, generally pink in color and very fine grained, even under the microscope, and consisting of orthoclase and calcite and masses of more coarsely crystalline epidote or diopside. These masses are probably closely related in origin to the syenitic form of the diorite, described as diopside-orthoclasite, an analysis of which is given in the table on page 40 (analysis 6).

Tremolite and diopside are found along the contact of the intrusive rock with massive limestone; wollastonite appears near the shaly limestones and is accompanied by much garnet and little or no diopside. The bands of garnet are sharply separated from the bands of wollastonite, the garnet probably occupying the place of shaly bands and the wollastonite that of the purer limestone. The absence of both tremolite and diopside near the shaly limestone is probably due to its lack of magnesia. Both these minerals are calcium-magnesium silicates, but wollastonite is a calcium silicate.

The contact rock is richer than either of the rocks inclosing it in ferric oxide, which is abundantly present in the garnet, and must have been introduced by the solutions that caused the contact metamorphism and the deposition of the ores.

The analysis of the contact rock in the contact deposits on Kasaan Peninsula does not show a great change in composition (see analysis, p. 83) because of the similarity in composition of the intrusive diorite and the intruded graywackes. The ore bodies, however, show that the copper and iron oxides and sulphides were introduced by the mineral-bearing solutions.

DEVELOPMENT OF THE ORE MINERALS.

The ore minerals occur chiefly near the limestone contact. With garnet and diopside, pyrrhotite and chalcopyrite are locally abundant in the recrystallized limestone. These ore minerals ramify in a meshlike structure through the calcite that incloses the diopside and garnet, and, in places, the amphibole. Finely outlined crystals of diopside are scattered thickly through the ore at some places in precisely the same manner as in the limestone. In other places, as at the Sultana claim, the ore occurs in parting and cleavage planes in shattered crystals of diopside and in veinlets of garnet. In a specimen from the Jumbo No. 4 claim the garnets that occur in the compact limestone of the wall rock are surrounded by thin shells of chalcopyrite.

Chalcopyrite occurs sparingly in the altered diorite in close association with calcite, which has been introduced into the diorite. Chalcopyrite and pyrrhotite are irregularly distributed in veinlike masses through that part of the contact zone which consists largely of garnet, diopside, orthoclase, calcite, and epidote. As developed in the contact rock this ore replaces calcite but not to any notable extent the other minerals.

In certain places the sulphide ores occur in distinct veins in the contact zone associated with epidote, quartz, orthoclase, calcite, a dark amphibole, magnetite, and, to less extent, diopside and garnet.

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[1] The term "replacement" is used in this report in its broadest sense, meaning "taking the place of," without implying that solution and deposition have been practically simultaneous. However, the microscopic evidence that the plagioclase of the diorite altered directly to scapolite is as clear as could be desired.

PROGRESS OF MINERALIZATION.

The following view of the progress of mineralization in the contact zones is favored by the evidence. In the limestone tremolite (or wollastonite) and diopside were formed by the introduction of silica; later, and in part contemporaneously, garnet was formed by the combination of the lime (already present) with silica, ferric iron, and alumina, introduced by solution. While the quartz and feldspars were being removed from the diorite calcite, garnet, and pyroxene (diopside) were added. Afterward chalcopyrite and pyrrhotite replaced part of the calcite in the contact zone without notably affecting the other minerals. Later the fissures, which probably held the solutions during the period of active metamorphism, were filled with pyrite, chalcopyrite, magnetite, and the other minerals above enumerated. Finally upon the older vein minerals were deposited notably zeolite and calcite.

PROBABLE LIMITS OF TEMPERATURE.

The probable limits of temperature between which contact metamorphism took place can not be very closely determined. Wollastonite, which, for reasons already stated, appears to have been one of the first minerals formed in the contact zone, can not exist above 1190° C.[1] The garnet, some of which probably formed almost contemporaneously with the wollastonite, is a variety having distinct double refraction. Experiments made with this garnet by Dr. Merwin at the Geophysical Laboratory of the Carnegie Institution of Washington show that it loses its birefringence after it has been heated for a few hours at about 800° C., and does not regain it after several hours heating at 600° C. This fact indicates that most of the metamorphism took place at temperatures lower than 800° C.

Quartz occurs in the contact zone only in veins. Tests made on some of this vein quartz by F. E. Wright, according to the method described by Wright and Larsen,[2] indicated that it was formed at temperatures below 575° C. The vein quartz was formed, however, during the last stages of metamorphic activity.

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[1] Allen, E. T., and White, W. R., On wollastonite and pseudowollastonite: Am. Jour. Sci., 4th ser., vol. 21, p. 89, 1906.

[2] Wright, F. E., and Larsen, E. S., Quartz as a geologic thermometer: Idem, vol. 27, pp. 421-447, 1906.

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DEPARTMENT OF THE INTERIOR
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THE ORIGIN OF COLEMANITE DEPOSITS

BY

HOYT S. GALE

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PREFACE.

The present paper is the first of a new series to be published by the Geological Survey under the title "Contributions to general geology." Of late years Survey authors have become contributors to scientific and technical journals to an extent that suggests the need of an official channel for papers of a certain type. Contribution to these outside journals is a valuable phase of the Survey's activity and will continue; but this method of publication has certain limitations by reason of both the capacity and the circulation of these journals. The time has come for beginning a volume that will afford opportunity for the publication of short papers and preliminary reports of a character not well adapted to publication in any of the forms heretofore used by the Survey.

It is significant that so many of the Survey geologists are making scientific contributions of general interest that represent results incidental to other investigations or that are of the nature of by-products of work whose immediate purpose is economic. This is because the so-called economic work of the Survey is really scientific. It is scientific in method and scientific in results. It represents the application of science to the solution of problems whose main bearing may be utilitarian but which, if successfully solved, will afford by-products in results and principles that will yield greater ultimate possibilities of use to man. In order to encourage greater breadth of observation and investigation among the geologists and to promote the scientific possibilities of their professional work, means should be provided for prompt publication of such papers in a permanent form that will commend itself to both author and reader. Provision has been made since 1902 for the current publication of short papers relating specifically to economic geology, and the new series here established is intended to make similar provision for scientific papers relating to general geology.

In advance of the printing of the full volume, separates, each including one or more papers, will be issued to the number of 10 or 12 a year as the manuscript and illustrations are ready, without waiting for material for the full volume to be in hand or even promised. These separates will be paged continuously, so that the volume will be simply a consolidation of the separates, without change of pagination, a distinct advantage for bibliographic reference. The date of publication will be printed on the title-page of each separate.

The papers included in these "Contributions to general geology" may relate to any phase of geology, provided it possesses general interest—petrology, paleontology, stratigraphy, glaciology, structural geology, etc. This volume is intended not as a catch-all for current odds and ends, but as a dignified collection of scientific contributions, each worthy in importance of subject, value of results, and quality of treatment for separate publication as a bulletin or professional paper if it were of sufficient length.

CONTRIBUTIONS TO GENERAL GEOLOGY, 1913.

THE ORIGIN OF COLEMANITE DEPOSITS.

By Hoyt S. Gale.

INTRODUCTION.

A brief study of several of the more important borate deposits in southern California during 1912 has suggested to the writer some ideas believed to be new regarding the origin of colemanite. The theory presented here has not yet been entirely proved, but as there is much in its favor and as it affords suggestions and a working basis for further observation, which the writer also hopes to have opportunity to make, it seems proper to place the matter briefly on record.

This paper is based chiefly on a short personal study of the borate deposits in Ventura County, Cal., supplemented by more cursory examinations of similar deposits in the vicinity of Death Valley, and includes a review of published data on this subject and of personal communications from those who have visited deposits elsewhere. A report discussing the economic geology of the colemanite deposits of Ventura County and the mining operations on them will appear in another place.[1] It is believed that these deposits afford exceptional opportunities for the study of the relationships of the colemanite ores.

VOLCANIC ORIGIN OF BORIC ACID.

It is generally recognized that boric acid in considerable quantities is an original constituent in the waters and gases given off with volcanic emanations. In fact, the Tuscan fumaroles have been an important commercial source of boric acid in Italy for a long time, and in the past, possibly even to the present time, almost all the boric acid brought into the European market was derived from this source. There is abundant evidence of the presence of boric acid in volcanic emanations in many parts of the world. On the other hand, boron is so rare a constituent of rock-forming minerals that it forms an almost inappreciably small percentage of the earth's rock mass as a whole. It is therefore natural in studying the genesis of boron minerals or deposits to look primarily for evidence of a possible origin in volcanic emanations. Such an origin is believed to be in fact strongly indicated by the relations to be observed in most borate deposits that have been studied.

HYPOTHESES REGARDING ORIGIN OF COLEMANITE.

The immediate origin of the colemanite ores of the southern part of the Great Basin has been discussed by several writers and geologists. W. H. Storms was perhaps the first to provide the explanation which has been more or less fully accepted since. In describing the deposits at Calico, near Daggett, Cal., he says:[2]

> To me it seems that what is now one of the most valuable deposits of mineral in the State was at one time the site of a Tertiary lake of considerable but as yet undetermined size; that although subjected to the same oscillation as the remainder of the region, a basin formed, in which the waters collected, carrying with them the mineral salts derived

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[1] Gale, Hoyt S., The borate deposits of Ventura County, Cal.: U. S. Geol. Survey Bull. 540-O, 1913.

[2] Storms, W. H., Mineral resources of San Bernardino County, Cal.: California State Min. Bur. Eleventh Ann. Rept., p. 346, 1893.

> from the rocks of the neighboring country, that finally the climatic conditions became such that the supply of water was less than the loss by absorption and evaporation, and the waters of the lake slowly diminished, it finally disappearing entirely, leaving on the floor of the lake a thick deposit of calcium borate of snowy whiteness.
>
> After the deposition of the borax bed a general subsidence of the region occurred, the waters of the great Tertiary lake once more covering the whole country. Again the sands and finer sedimentary material—the erosion of the mountains—were carried down and found a resting place on the floor of the lake, the borax beds being finally covered.

Subsequent deformation of these strata has tilted and erosion exposed the borate beds.

Campbell [1] adopted a similar explanation of the genesis of the deposits at the same locality:

> The borax of Death Valley, as well as that near Daggett, occurs in a regular stratum, interbedded with the semi-indurated sands and clays that make up the bulk of the strata. These beds are generally regarded as of Tertiary age, and they are supposed to have been deposited in inclosed bodies of water.
>
> * * * * * * * * *
>
> The principal deposit of boron salts [near Daggett] occurs at Borate, about 12 miles north of Daggett, in the vicinity of the old Calico mining district. The mineral found here is borate of lime, or colemanite, and it occurs as a bedded deposit from 5 to 30 feet in thickness, interstratified in lake sediments.

Spurr,[2] in discussing the character and formation of the Tertiary lake beds, says, with special reference to the borate of lime deposits: "The internal evidence of these beds shows that much of the material was laid down in inclosed lake basins, and that the colemanite beds are probably the result of the evaporation of Tertiary alkaline lakes during periods of aridity."

Later Keyes [3] suggested a modification of the hypothesis by assuming the Tertiary water bodies to have been marine, "a great shallow arm of the Pacific Ocean that had been cut off by the upheaval of the mountain ranges along the coast." As the fossils obtained from the sedimentary beds associated with the borates, at least in the Mohave Desert, indicate a land and fresh-water fauna exclusively, this modification of the hypothesis may probably be dismissed.

Baker [4] discusses at some length the character of the sediments associated with the borate deposits and refers to the genesis of borate ores near Daggett:

> The interbedded layers of colemanite, gypsum, and limestone were most probably deposited on the evaporation of a body of water of considerable depth, since the colemanite layer is from 5 to 30 feet in thickness. Layers of pure gypsum several inches thick are found, as well as more considerable thicknesses of what is probably chemically deposited limestone. An alternative hypothesis, that these minerals had their immediate origin in hot springs and solfataras opening directly into shallow lakes, perhaps only of seasonal duration, or in playas, has much to commend it, especially when considered in connection with the numerous evidences of shallow-water deposition. These evidences comprise ripple marks, sun cracks, rain prints, found on the finer as well as the coarser beds, and the layers of fine breccia and conglomerates interbedded with the fine shales and tuffs. Shallow lakes or ponds probably existed at times during the deposition of the fossiliferous tuff member, for they seem to be necessary to account for the presence of the gastropods. The paucity or absence of fossils in the borate and the fine ashy and shaly tuff members (but one specimen of a Planorbis was found in these beds), as well as the presence of the colemanite, limestone, and gypsum layers, apparently indicates the salinity of the waters. * * * Colemanite, gypsum, and limestone were deposited either by hot springs or solfataras in saline lakes, which might have been of shallow depth, or, having leached from the surrounding rocks, were precipitated during a time or times of evaporation of a former fresh-water lake of considerable depth.

Lately Eakle [5] has described the colemanite mined at Lang and summarized the origin of the deposit as follows:

> The bedded character of the deposit is evidence that the mineral crystallized from an evaporating solution, and that precipitations of both the borate and some of the silt which formed the shales took place. The solution filled a closed basin as a lake or marsh, probably similar to the alkali marshes of the desert regions. It is generally characteristic of such deposits that salts of various kinds, often in alternating series, especially carbonates and sulphates of lime and soda, make up the deposit, and the well known Searles borax lake in San Bernardino County, with its many associated minerals, is a good illustration of a desert formation. The Lang deposit, however, is an exception, as the neocolemanite is practically unaccompanied by other minerals, except howlite, which is a silico-colemanite, and some calcite. Waters emptying into the basin could not have been charged with mixed alkali salts.
>
> It seems probable that the original site of the deposit was a marsh containing marl and calc tufa with mud and considerable organic growth, and that later waters charged with boracic acid flowed into the basin and converted the

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[1] Campbell, M. R., Reconnaissance of the borax deposits of Death Valley and Mohave Desert: U. S. Geol. Survey Bull. 200, pp. 8, 12, 1902.

[2] Spurr, J. E., Ore deposits of the Silver Peak quadrangle, Nevada: U. S. Geol. Survey Prof. Paper 55, p. 21, 1906.

[3] Keyes, C. R., Borax deposits of the United States: Am. Inst. Min. Eng. Bull. 34, 1909.

[4] Baker, C. L., Cenozoic history of the Mohave Desert: Univ. California Dept. Geology Bull., vol. 6, No. 15, 1911.

[5] Eakle, A. S., Neo-colemanite, a variety of colemanite, and howlite from Lang, Los Angeles County, Cal.: Univ. California Dept. Geology Bull. vol. 6, No. 9, 1911, pp. 179–189.

carbonate of lime into the borate. Some and perhaps the greater part of the argillaceous material which forms the shales was precipitated by the decomposition of the impure limestone, together with organic matter. The carbon dioxide set free may not wholly have escaped, but possibly became occluded in the mud and later converted into carbon. Most of the borate is of a blackish-gray color, due to impregnations of carbon along the cleavages and fractures. The conversion of the limestone into the borate in all probability took place before the overlying sandstones were formed. The absence of soda compounds and the presence of abundant plant life indicate that the lake or marsh was fresh, into which springs containing boric acid discharged. The deposit later became submerged and the sandstones were laid down.

The origin of the boric acid is presumably volcanic and the springs probably issued from vents in the immediate vicinity of the basin. The deposit is situated in a hilly district and is partly surrounded by high masses of volcanic tuffs and rhyolites. The subsequent tilting of the deposit was not accompanied by heat or pressure sufficient to modify the borate materially, yet the mineral shows lines of strain and columnar partings due to pressure and shrinkage. The fissile shales owe their solidity to this slight pressure, and carbonization to some extent was also the result. There is, of course, the possibility that all of the carbon in the deposit is from organic matter, the CO_2 of the carbonate escaping, as some of the shales are quite bituminous.

Eakle does not mention any immediate relation of the deposit to lavas, such as are known to be intimately associated with borate-bearing beds elsewhere, although he notes that the Lang district is partly surrounded by high masses of volcanic tuffs and rhyolites.

Study of the colemanite deposits in Ventura County, Cal., and observations on similar deposits near Death Valley have led the writer to the conclusion that these borate minerals and probably also most of the gypsum associated with them are vein deposits and not the product of evaporated lake waters. The evidence supporting this conclusion is set forth briefly below.

COLEMANITE DEPOSITS OF VENTURA COUNTY, CAL.

The Ventura County deposits of colemanite lie on the southern flank of Mount Pinos, near the San Emigdio Range, at the south end of the San Joaquin Valley. The colemanite is found within a series of bedded rock formations, which have been extensively folded and faulted. In general the trend of their outcrop is northeast and southwest, and the dip southeastward, away from the higher elevations of the Mount Pinos Range.

The section of sedimentary beds and lava with which the colemanite is associated is in general terms as follows:

Section of formations in which colemanite occurs in Ventura County, Cal.

Top of section measured.	Feet.
Shale and some sandstone	300
Basaltic lava flows, with intercalated layers or lenses of shale and limestone	600
Shale	600
Conglomerate, bowlders, or cobbles of light granitic rock cemented	600
Other sedimentary rocks below.	

These beds are believed to be of Miocene age. The more extensive stratigraphic section exposed in this general region has not been included here, as its possible relation to the borate ores seems remote and it evidently involves many complex problems. The beds defined above are apparently conformable. The most valuable borate deposits are included within the layers of shale and limestone intercalated within the flows of basalt, but borates occur also in the shales above and below the basaltic flow rock, though invariably in close association with this lava.

The following interpretation may be placed on the section given above. The base of the section is a massive conglomerate made up of bowlders or more or less rounded cobbles, in part very firmly cemented together, and the whole mass constitutes a rather distinct formational unit. This is supposed to be a piedmont alluvial deposit that was originally spread out from the base of the Mount Pinos Range. The core of the range is believed to be mainly granite of the character represented by the bowlders of this formation. The bowlders are coarser near the mountains and seem to grade off to finer material at greater distance, the formation as a whole taking on the character of sandstone, as illustrated at the Ives camp, at the lower end of the Middle Fork canyon. There seems little evidence in this formation to indicate other than subaerial distribution of very coarse detrital material. However, in the opinion of R. W. Pack, who has studied the areal geology of the north slope of the San Emigdio Range, there may exist some room for doubt that the coarse gravels were deposited subaerially. On the north slope of that range about 10 miles north of the borax mines he has found coarse conglomerate beds containing granitic bowlders several feet in diameter interstratified with fine sandstones and sandy and diatomaceous shales, the latter containing marine fossils of Miocene age. The coarse beds occur at several horizons and are so intimately associated with the fossiliferous strata as to suggest that the whole section is marine.

The shale overlying the bowlder conglomerate and sandstone is light-colored detrital material, thin bedded, and so readily eroded that it does not form conspicuous exposures. It has not been examined in detail, but it is supposed to be made up of muds derived by the more complete comminution of granitic material similar to the granite in composition. It may be a delta plain or alluvial deposit distributed by quieter waters than those which carried out the bowlder wash, or it may have been deposited under water. At present there is no conclusive evidence as to its origin.

Overlying the shale is a massive accumulation of flows of basaltic lava, with vesicular and slaggy layers. Evidently many distinct flows are represented in the thickness of some 600 feet measured on North Fork. These flows include several intercalated layers of shale and limestone, with which the most valuable colemanite deposits of the district are associated.

The basalt is overlain by another mass of shale and sandstone similar to that which underlies it. The history represented by these beds may be much like that which preceded the outpourings of the lava.

The colemanite of Ventura County is evidently typical of the mineral as it occurs elsewhere. It is found in solid crystalline masses of large size but of very irregular form. The mineral itself in its purest form is milky white, even glassy in part, much resembling pure-white calcite in general appearance and cleavage. The crystal forms are, however, quite distinct from those of calcite. The less pure massive ore includes grayish or even black crystalline bodies, the color of which is supposed to be due to included impurity.

The mineral masses as a whole are of very irregular form, but they have been generally described as bedded deposits, for they appear to follow the bedding of the sedimentary strata with which they are associated. When examined in detail, however, the mineral colemanite does not exhibit any bedding structure but only the forms characteristic of the crystallization of the mineral itself. The massive deposits are either crystalline without definite arrangement or show radial structures as well as seams of definitely vein-banded material, included between walls, in places containing open cavities lined with crystal terminations. The irregularity or bunchy character of the deposits alone would prohibit strict parallelism with the distinctly bedded shales in which they are included. Other evidence afforded by the deposits themselves is suggestive of formation in veins, as will be pointed out.

The larger deposits of colemanite, such as those of the Columbus, Russell, and Frazier mines, are associated with shale and limestone lenses included within the section of basalt lava flows. In each of the mines mentioned the colemanite ore appears to have been developed in immediate association with a bed of limestone included within the shale. This limestone is massive or of rough, porous character on the weathered outcrop, suggesting the designation "travertine-like." Basaltic lava occurs stratigraphically above and below the ore bodies and is generally encountered in the mine workings not far from the ore. The shale bands intercalated within the basalt flows much resemble the shales that both overlie and underlie the whole sequence of flows.

The present attitude of the beds that include the ore bodies ranges from nearly flat to steeply dipping. The nearly horizontal ore bodies in the Frazier mine are the development of beds near the crest of an anticlinal fold. In general the rocks dip steeply.

In one large deposit examined underground (in the Russell mine) the main ore body follows a zone of slip faulting, which is also approximately parallel to the bedding, the ore being limited with much distinctness by a wall of slickensided gouge.

The outcrops have rarely shown any colemanite, even in the ore-bearing zone. The one exception noted, that of the original discovery at the Frazier mine, was an exposure near the top of a very steep bluff in which a great amount of slipping had taken place and normal outcrops were not present. Possibly a minor amount of the borate minerals is also present elsewhere in the outcropping strata, but it is very inconspicuous and was not observed. As a rule the outcrop of the borate-bearing beds is either folded and crumpled shale or shale including a massive limestone ledge, the limestone forming the most conspicuous part of the outcrop. These zones are generally indicated by an abundance of gypsum, which is a marker followed in prospecting and occurs in the form of thin stringers included in the opened bedding planes and in cross fractures of the shale. All the gypsum is of the clear crystalline variety selenite, and no massive bedded deposits of gypsum are known in this region. The outcrops of these gypsiferous shales are also characteristically marked by the occurrence of "button" concretions flattened spheroidal nodules or disks of calcareous composition that have very commonly been mistaken for fossils. The occurrence of these concretions at the outcrop of the basaltic lava, in the immediate vicinity of the ore-bearing zones, usually only a few feet distant, is believed to be significant and is generally noted and referred to by the prospector. As a rule, however, the prospector regards the lava as an intrusive "porphyry," which it clearly is not, as attested by its common vesicular and amygdaloidal character, as well as its distinctly bedded structure, conformable with the sedimentary strata.

Certain specimens collected on the ore dumps and in the mines show that at least a part of the colemanite is a replacement deposit. Irregular portions of the limestone are surrounded by white crystalline colemanite, and minute fractures which traverse the limestone throughout are also filled with this mineral. These veinlets are observed to have been enlarged irregularly within the limestone. Small rounded masses of limestone are also included within the solid portions of the colemanite, indicating that in places the same enlargement of intersecting veinlets has been carried to a further stage and the separated limestone portions are residual within the deposited colemanite.

GENERAL EVIDENCE OF VEIN CHARACTER OF COLEMANITE DEPOSITS.

The direct evidence of the character of the colemanite, of course, lies in the deposits themselves. If the deposits are of vein form, the evidence suggesting it has hitherto been overlooked. In natural outcrops relationships are obscure. The study of the ore in place is not facilitated by conditions at the mines. The old mining entries on the Ventura County deposits were, when visited, either inaccessible or, if open, were heavily timbered, dripping with water, and coated with mud, so that they were not favorable to detailed study of the character of the ore. The facts of observation therefore are not yet to be considered conclusive, and judgment as to whether these deposits originated as veins or through desiccation involves a study of other more general considerations.

Colemanite, the borate of lime, is relatively insoluble in water. A recent determination, made at the writer's suggestion by W. B. Hicks in the Geological Survey laboratory, of the solubility of certain specimens of apparently pure colemanite from the Ventura County deposits has shown that at ordinary temperatures (20° to 25° C.) about 1 part is soluble in about 1,100 parts of water. Van 't Hoff has shown that colemanite may be produced artificially by reactions from other calcium borates in saturated alkali chloride solutions, but the writer knows of no data concerning the possible formation of this mineral by direct reaction of boric acid and limestone. It is natural to assume that free boric acid, which is a common constituent of the later volcanic emanations in this general region, might react with limestone, and that by the substitution of boric for carbonic acid the lime borate would be formed. Thus by a process of metasomatic replacement might have been formed deposits of the typical irregular character of the known colemanite masses, roughly following the bedding of the original calcareous rock or of the interbedded lenticular bodies of limestone. Therefore in so far as the natural reactions are concerned the formation of colemanite as fissure and replacement vein deposits is well within the limits of possibility. But for other reasons also it seems that these colemanite deposits are not logically to be ascribed to deposition as the principal constituent of a residue derived from the waters of a desiccating saline lake.

Borates have been shown to exist in natural saline waters and desiccation deposits in many parts of the Great Basin and the desert country of the western United States. So far as known to the writer, however, colemanite has nowhere been deposited as a result of desiccation, but rather the boric acid has combined to form the more common surface saline minerals, such as ulexite and tincal. Is it therefore reasonable to suppose that ulexite, tincal, etc., could have been the primary deposits of such Tertiary dry-lake formations, from which colemanite had subsequently formed as a secondary product? If this had been so, would not some evidence of the primary deposit be at hand, either in the composition or in the structure of some parts of the colemanite deposits? Such evidence has not been recorded.

If colemanite were but a part of a natural saline residue deposited by the desiccation of the waters in which these materials had accumulated and become concentrated, it would be most natural to expect other salines that are commonly more abundant than the salts of boric acid in the typical desiccation deposits of the desert region. No appreciable amount of bedded salt, sodium sulphate, or carbonate is to be found with the colemanite deposits known to the writer. The borate-bearing shales of the Ventura County deposits are not even of a character that might be described as "alkaline" in ordinary desert parlance.

Gypsum and limestone, the latter travertine-like, occur in association with the borates, and former writings have already been quoted to the effect that both are chemical residues derived from the same desiccation that crystallized the colemanite. The gypsum associated with the borate-bearing shales is crystalline selenite. All or the greater part of it occurs in thin stringers, which not only follow the bedding joints of the shales but fill transverse fractures. The cross-fiber structure of much of this selenite is evidence of its deposition in veins. No rock gypsum of distinctively sedimentary character was observed in any of these beds. Gypsum is being deposited from ground waters along the walls of the mining entries at the present time. It still remains to be proved, therefore, that any gypsum of original sedimentary character is included with the borate-bearing deposits. All of this mineral present may have been introduced in solution by percolating ground waters. The stringers of gypsum noted so abundantly in the outcrops of the borate-bearing shales have not been shown to persist in like quantity in the few deeper developments of the mining entries.

The limestone strata with which the principal colemanite ore bodies are associated are evidently original in the sedimentary sequence. They are in part at least travertine-like, weathering in rough tufa-like surfaces, and are not compact like more typical limestones. Their character suggests the probability that they are chemical deposits, possibly of local extent, laid down in shallow waters, being similar to the travertine deposits now forming near springs or where ground waters flow into ponds or saline lakes. The limestone masses are believed to be of lenticular form and to occur interbedded with shales at various horizons within the flows of basaltic lava. They are not necessarily the product of desiccation.

In fact, there is little evidence from the stratigraphic section associated with the borate beds of Ventura County that can be taken to indicate the extensive lacustral conditions commonly assumed to have existed during the Miocene epoch in the Tertiary. Some of the associated deposits may have been "lake beds," but the writer believes rather that the submergences were the result of local, temporary, and variable conditions, such as may have occurred during or after periods of shallow flooding in the lower portions of piedmont fluviatile plains.

Lastly, an explanation of the source of the boric acid is to be sought. Naturally, a volcanic origin is suggested, and in Ventura County the association of the colemanite with the basaltic lava is certainly intimate. It is a common saying among prospectors of the district that "borax" will not be found except near a "porphyry contact" and in association with limestone. It is true that the larger ore bodies mined are all in close relation with some part of the basaltic lava flow rock in place, generally within a few feet of it. The borate-bearing beds follow the outcrop of the basalt flows throughout the district. The question in what way boric acid originating with the extrusion of these flows could have caused reactions and mineral deposition soon or long after the period of the lava extrusion remains for further investigation.

SUMMARY.

The evidence favoring the hypothesis of a desiccated saline lake to explain the origin of the colemanite has little to support it beyond rather general assumptions. The actual character of the deposits themselves indicates rather a vein type of formation. The gypsum which has been pointed to as a desiccation deposit related to the colemanite is also of vein character. Other salines which would naturally be expected in desiccation deposits resulting from natural saline solutions are not found in association with the colemanite. Those who have supported the desiccation hypothesis have offered no explanation of the reaction which might produce colemanite in such massive deposits as a product of water evaporation, while, on the contrary, its formation from limestone in veins by replacement of carbonic acid with boric acid is a natural working hypothesis that deserves experimental investigation. The relations of the deposits to basalt lava flows indicate the probable origin of the boric acid at the time of the extrusion of these lavas, although it may also be necessary to assume that this acid continued to find its way into solution of the circulating ground waters long after the period of the lava extrusions.

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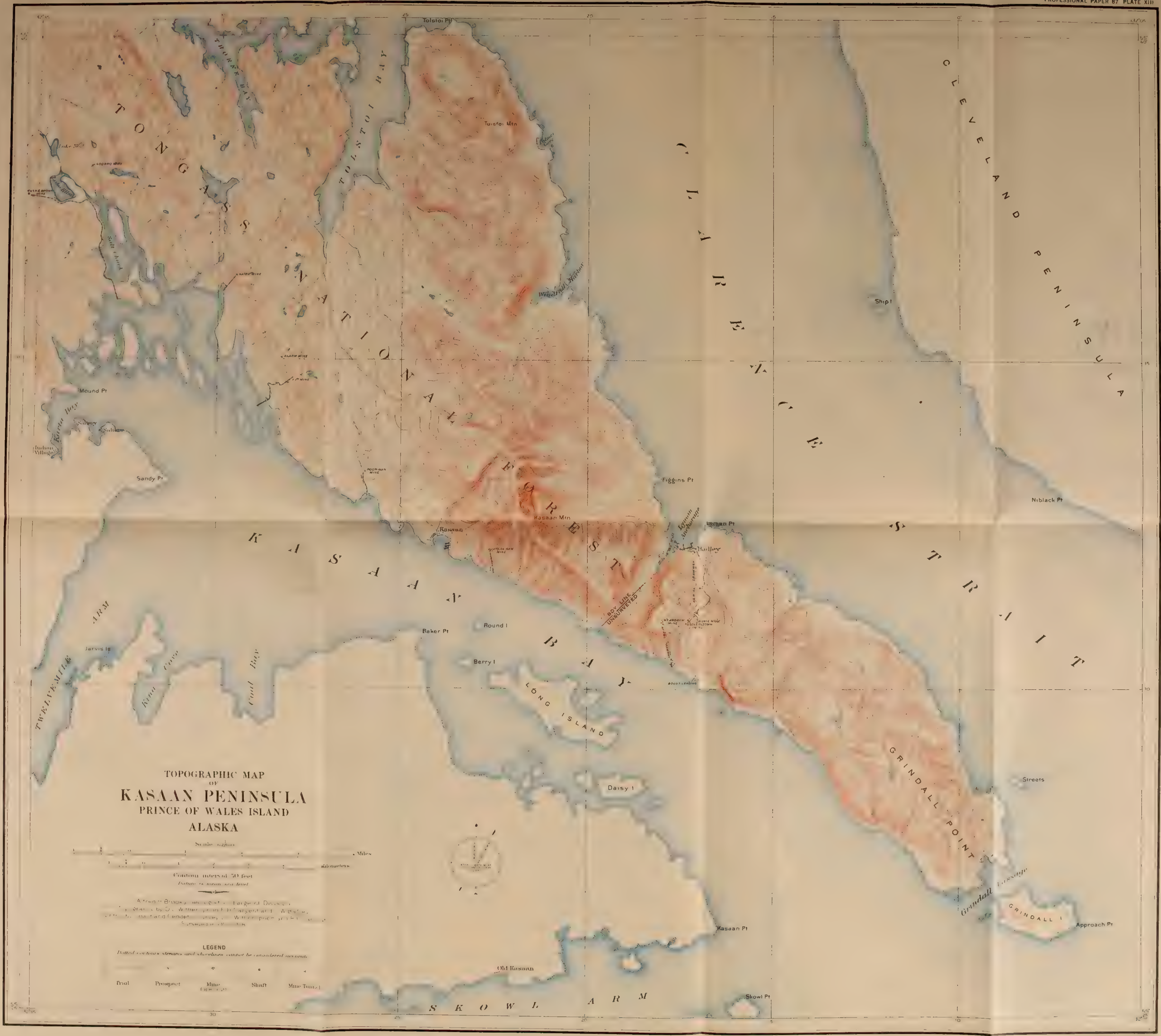
TOPOGRAPHIC MAP
OF
KASAAN PENINSULA
PRINCE OF WALES ISLAND
ALASKA
Scale
Miles
Kilometers
Contour interval 50 feet
Datum is mean sea level
LEGEND
Dotted contours streams and shorelines cannot be considered accurate
Trail
Prospect
Mine
Shaft
Mine Tunnel
TONGASS NATIONAL FOREST
CLARENCE STRAIT
CLEVELAND PENINSULA
KASAAN BAY
TWELVEMILE ARM
SKOWL ARM
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Thorne Bay
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UNSURVEYED
Round I
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Berry I
Jarvis Is
Kina Cove
Coal Bay
LONG ISLAND
Daisy I
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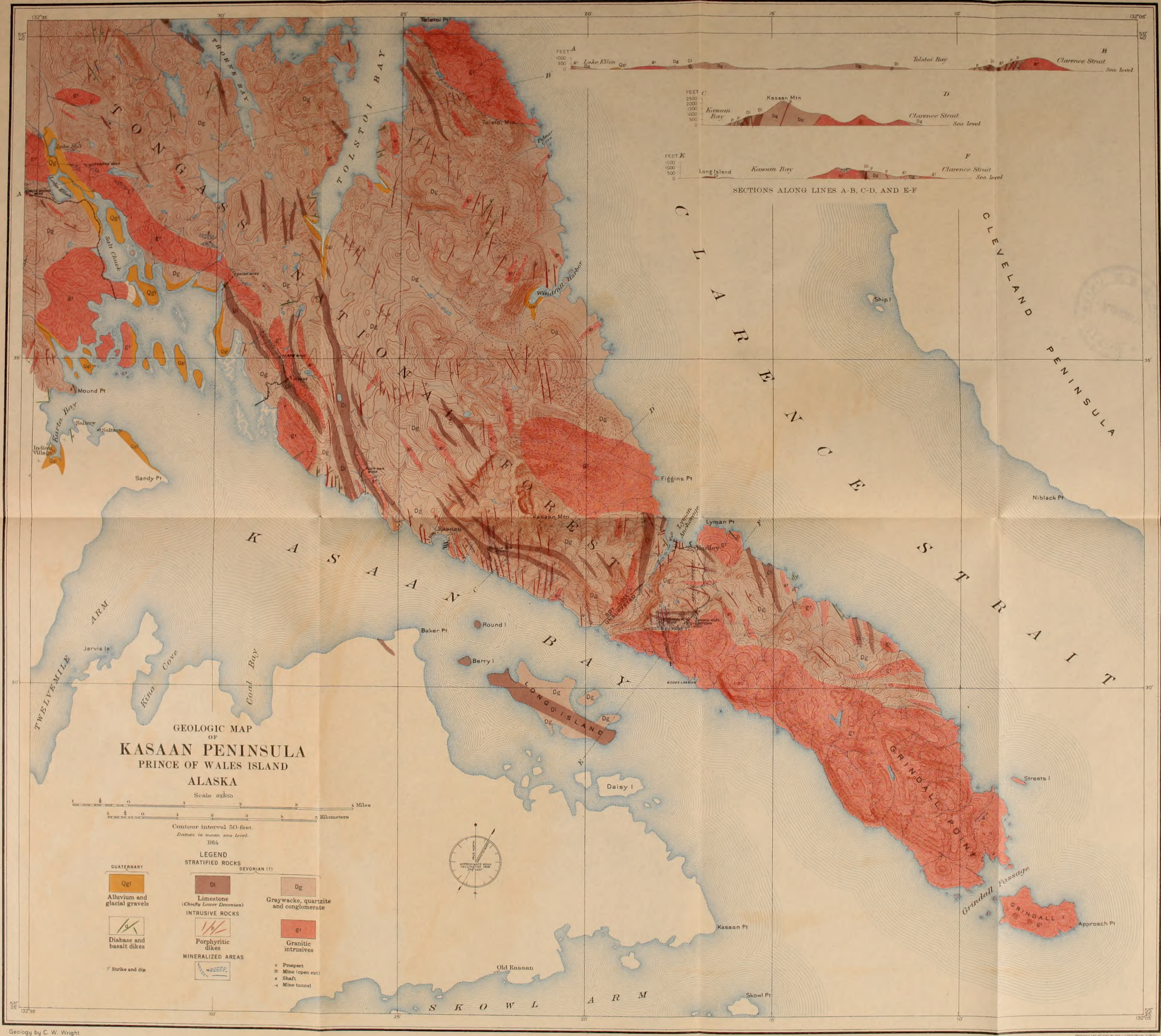

Geology by C. W. Wright
Surveyed in 1907-1908, under
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